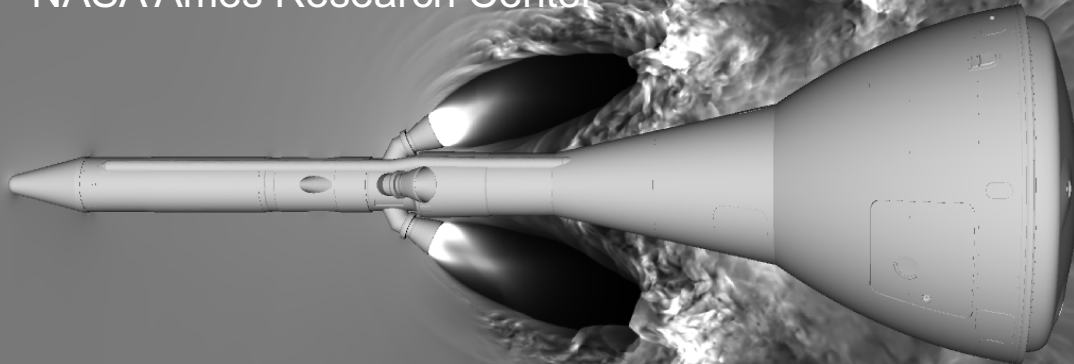# Orion Launch Abort Acoustics

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James Jensen, and Cetin Kiris
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NASA Ames Research Center

Pressure on the vertical plane (white is high, black is low) for Orion launch abort vehicle during ascent abort at transonic speed and high angle of attack

Advanced Modeling and Simulation (AMS) Seminar

NASA Ames Research Center, April 9, 2019

Outline

- Introduction

- Methodology

- Results:
    1) Pre-test computational fluid dynamics (CFD) support and post-test validation for Orion abort motor qualification ground test (QM-1)
    2) Using CFD to account for presence of Orion LAV surface in QM-1 test
    3) Investigation into ascent abort scenarios
    4) Wind tunnel CFD validation and scaling to flight conditions
    5) Using CFD to reduce uncertainty at high angles of attack

- Lessons learned

- Summary

National Aeronautics and Space Administration

ORION

Launch Abort System (LAS)

NASA**facts**

Ensuring Astronaut Safety

NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In order to keep astronauts safe in such difficult, yet exciting missions, NASA and Lockheed Martin collaborated to design and build the Launch Abort System.

Launch Abort System Configuration

The Launch Abort System, or LAS, is positioned atop the Orion crew module. It is designed to protect astronauts if a problem arises during launch by pulling the spacecraft away from a failing rocket. Weighing approximately 16,000 pounds, the LAS can activate within milliseconds to pull the vehicle to safety and position the module for a safe landing. The LAS is comprised of three solid propellant rocket motors: the abort motor, an attitude control motor, and a jettison motor.

JETTISON MOTOR - The jettison motor will pull the LAS away from the crew module, allowing Orion's parachutes to deploy and the spacecraft to land in the Pacific Ocean.

ATTITUDE CONTROL MOTOR - The attitude control motor, consists of a solid propellant gas generator, with eight proportional valves equally spaced around the outside of the three-foot diameter motor. Together, the valves can exert up to 7,000 pounds of steering force to the vehicle in any direction upon command from the Orion crew module.

ABORT MOTOR - In the worst-case scenario the abort motor is capable of producing about 400,000 pounds of thrust to propel the crew module away from the launch pad.

FAIRING ASSEMBLY - The fairing assembly is a lightweight composite structure that protects the capsule from the environment around it, whether it's heat, wind or acoustics.

FUN FACTS

- The Launch Abort System can activate within milliseconds to carry the crew to a peak height of approximately one mile at 42 times the speed of a drag race car.
- The Launch Abort System's abort motor generates enough thrust to lift 26 elephants off the ground.
- The Launch Abort System's abort motor produces the same power as five and a half F-22 Raptors combined.
- The Launch Abort System can move at transonic speeds that are nearly three times faster than the top speed of a fast sports car.
- The jettison motor can safely pull the Launch Abort System away from the crew module to a height of 240 Empire State Buildings stacked on top of each other.

4

Using HPC To Keep Astronauts Safe

1. Perform time-accurate, scale-resolving computational fluid dynamics (CFD) simulations to predict transient pressure loads in various sections of the Orion Launch Abort Vehicle (LAV) for a wide range of launch abort scenarios: pad abort, subsonic/transonic/supersonic ascent abort

2. Collaborate with Orion Loads and Dynamics team to combine:

   - CFD predictions
   - wind tunnel experiments   To better characterize and reduce uncertainty in the
   - ground test measurements   acoustic environment
   - flight test measurements

3. In the context of optimizing the design of the LAV fairing assembly:

   - Minimize Orion LAV fairing assembly structural weight
   - Reduce risk of structural failure due to vibrations

Initial Project Requirements

Predict transient pressure loads and acoustics on near field plume acoustics towers, heat shield cage structure, and crane ahead of QM-1 abort motor ground test

Picture from ST1 abort motor ground test

CFD Requirements

Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- Simulate complex geometry over large domain and long integration time for acoustics

- Track ignition overpressure (IOP) wave as it propagates

- Capture high Mach number turbulent plume acoustics
  - Turbulent jet shear layers responsible for majority of acoustics
  - Combustion noise is minimal

- Short turnaround time for decision making

CFD Grid Paradigms

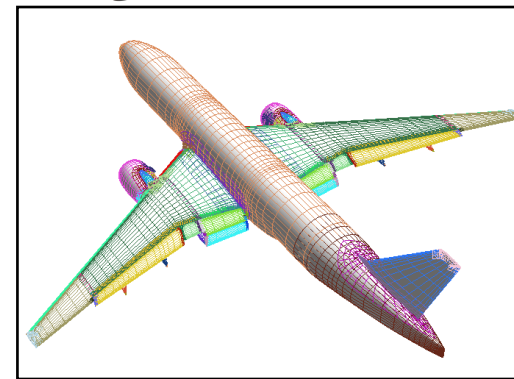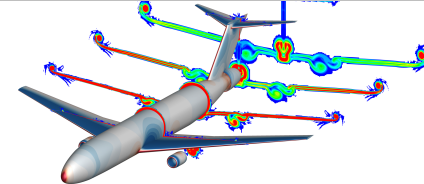| Structured Cartesian AMR	Unstructured Arbitrary Polyhedral	Structured Curvilinear
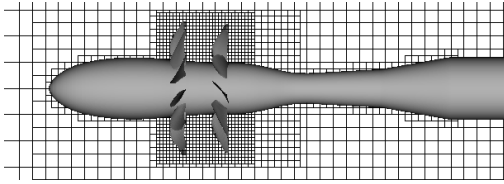
Structured Cartesian AMR
- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient
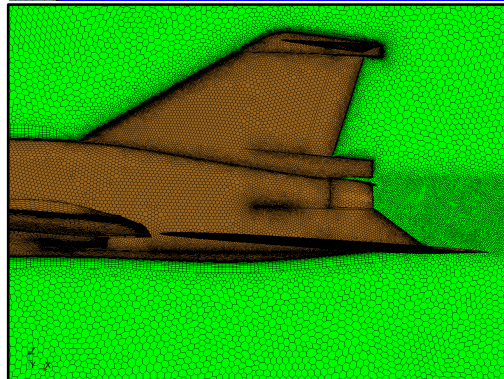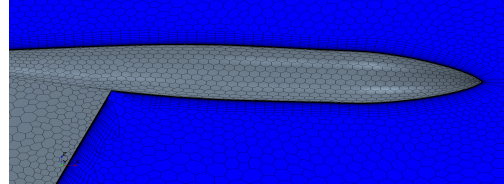
Unstructured Arbitrary Polyhedral
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
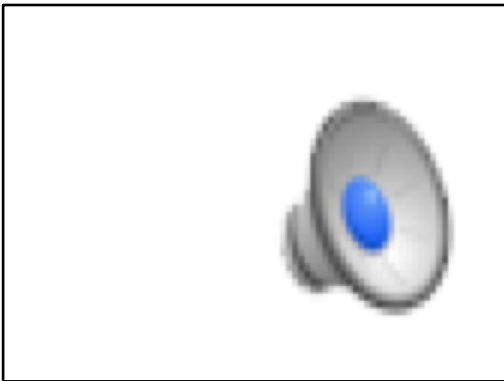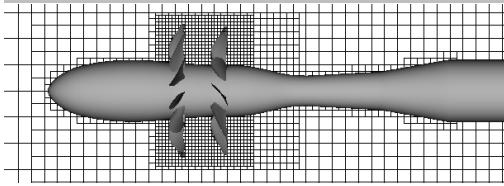- Higher order methods yet to fully mature

Structured Curvilinear
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Why Cartesian AMR?

Structured Cartesian AMR

- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
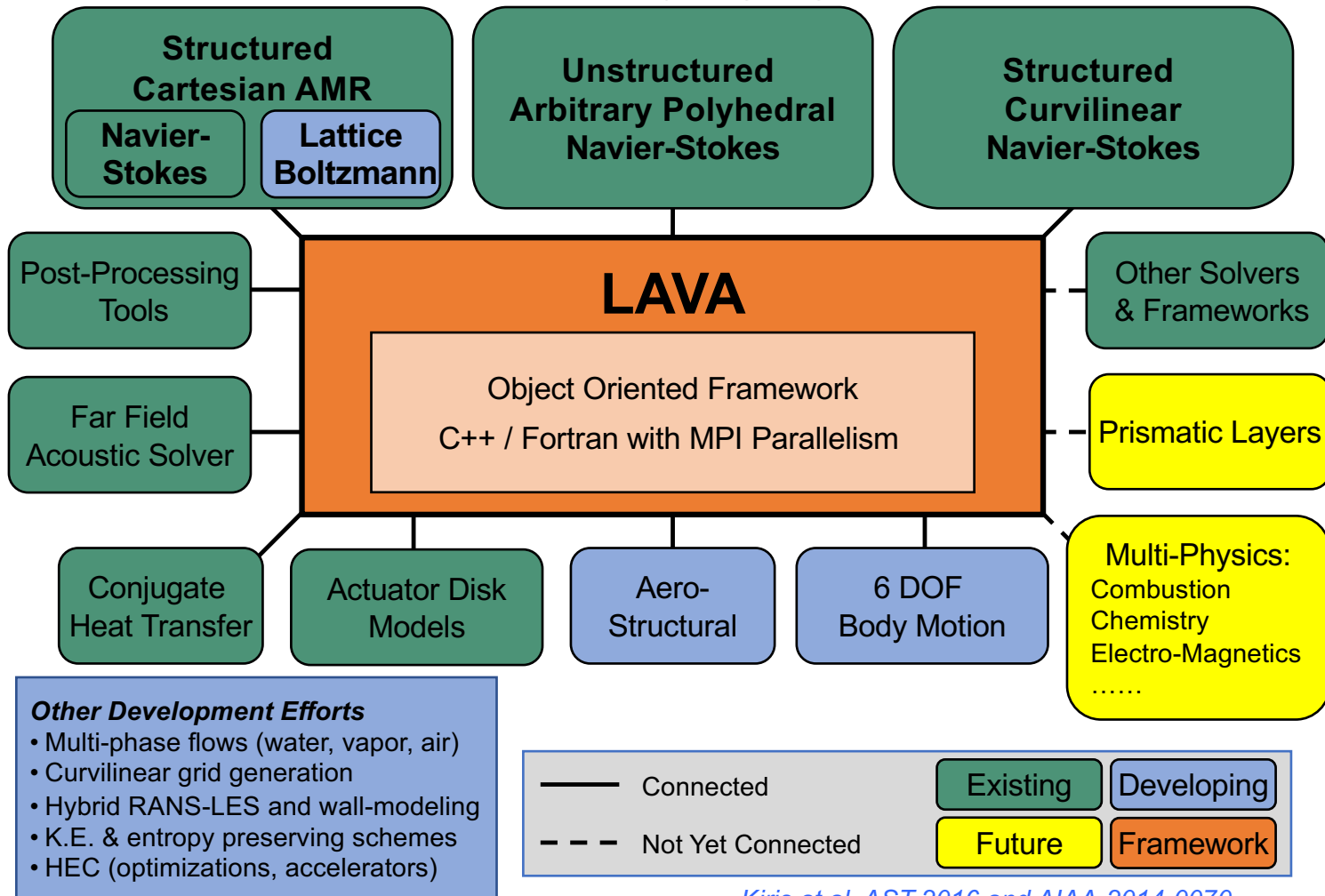- Non-body fitted -> Resolution of boundary layers inefficient

Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- Simulate complex geometry over large domain
  - ✓ Automatic mesh generation and immersed boundary representation
- Track ignition overpressure (IOP) wave as it propagates
  - ✓ On-the-fly solution-based adaptive mesh refinement (AMR)
- Capture high Mach number turbulent plume acoustics
  - ✓ Robust high-order scheme in space and time
  - ✓ Near-isotropic cells are best for predicting jet noise
  - ✓ Boundary layers do not play critical role for the quantities of interest for this project
- Short turnaround time for decision making
  - ✓ Automatic grid generation means we can get started immediately
  - ✓ Block-structured framework increases computational efficiency

# **L**aunch, **A**scent, and **V**ehicle **A**erodynamics
LAVA Framework

Structured Cartesian AMR
- **Navier-Stokes**
- **Lattice Boltzmann**

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

LAVA

Object Oriented Framework

C++ / Fortran with MPI Parallelism

Other Solvers & Frameworks

Prismatic Layers

Multi-Physics:
Combustion
Chemistry
Electro-Magnetics
......

Conjugate Heat Transfer

Actuator Disk Models

Aero-Structural

6 DOF Body Motion

Other Development Efforts
- Multi-phase flows (water, vapor, air)
- Curvilinear grid generation
- Hybrid RANS-LES and wall-modeling
- K.E. & entropy preserving schemes
- HEC (optimizations, accelerators)

—— Connected	Existing / Developing
- - - Not Yet Connected	Future / Framework

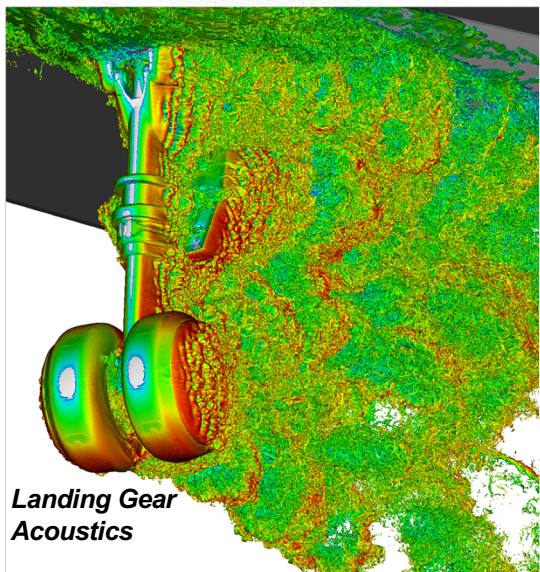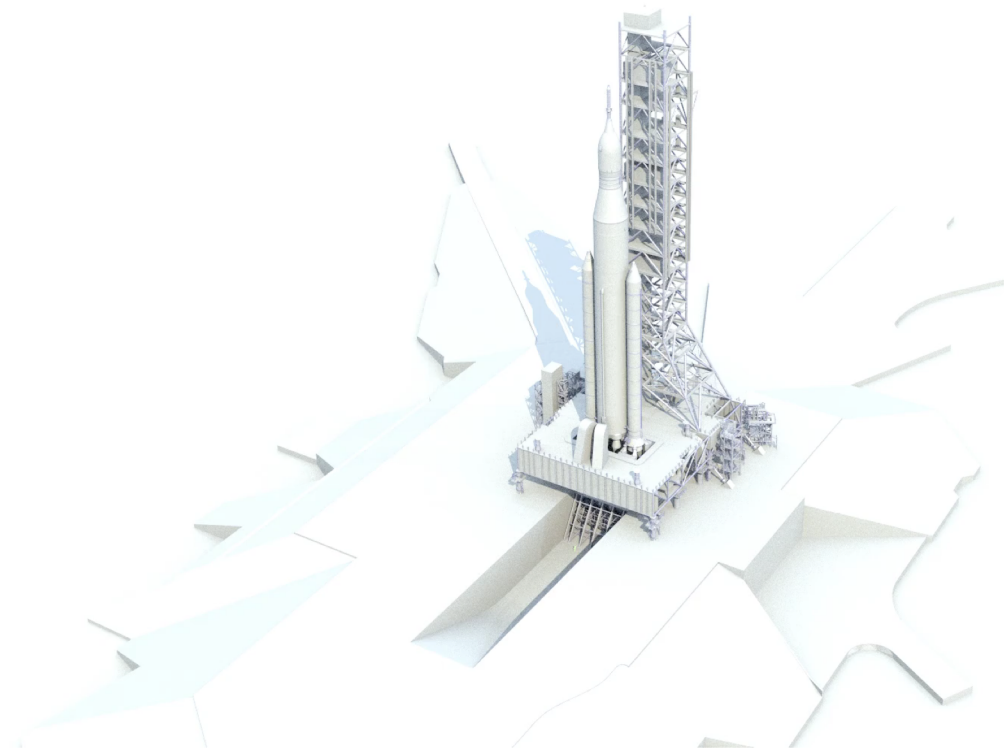*Kiris at al. AST-2016 and AIAA-2014-0070*

Previous LAVA Cartesian AMR Applications

SOFIA Airplane Cavity Acoustics
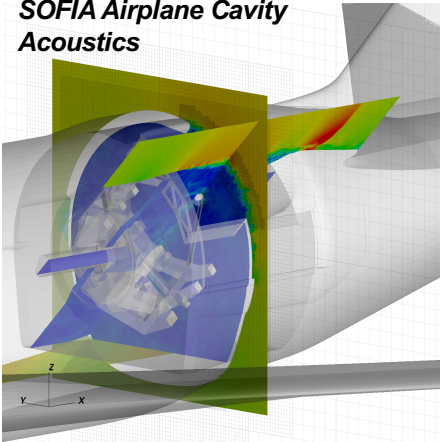
Kennedy Space Center Launch Pad 39B Flame Trench Redesign

Landing Gear Acoustics

Numerical Methodology

- Solve multi-species Navier-Stokes equations (no turbulence/subgrid scale model) with

  - 5th order weighted essentially non-oscillatory (WENO5) convective flux [1]

  - 2nd order centered viscous flux

  - explicit 4th order Runge-Kutta (RK4) time integration with CFL ~ 0.5

- Used immersed boundary method [2,3] with slip walls

- Motor modeled with exhaust mixture and time-varying total pressure and temperature conditions inside chamber provided by contractor's ballistics simulation (and then fixed operating point from test measurements)

[1] Brehm, Christoph, et al. "A comparison of higher-order finite-difference shock capturing schemes." *Computers & Fluids* 122 (2015): 184-208.
[2] Brehm, C., and Hermann F. Fasel. "A novel concept for the design of immersed interface methods." *Journal of Computational Physics* 242 (2013): 234-267.
[3] Mittal, Rajat, et al. "A versatile sharp interface immersed boundary method for incompressible flows with complex boundaries." *Journal of computational physics* 227.10 (2008): 4825-4852.

Grid Refinement Study

- Halved the finest grid spacing until we matched ignition over-pressure (IOP) from ST1 abort motor ground test data

- Obtained good match with ~0.02 nozzle diameters (D) cubes

- Fixed maximum mesh spacing on volumes around plumes and vehicle/test stand to ~0.04 D

- Used AMR with re-gridding every 10 steps ($\Delta t \sim 1.6 \times 10^{-6}$ seconds) to follow regions of high vorticity and pressure gradient magnitude with a cap on number of cells per level and total of 380 million cells

Example of AMR Mesh

- Taken from QM1v2 simulation at t=0.32 seconds after ignition
- Darkest patch is finest level with $\Delta x \sim 0.02$ nozzle diameter
- Subsequent levels are factors of 2 larger
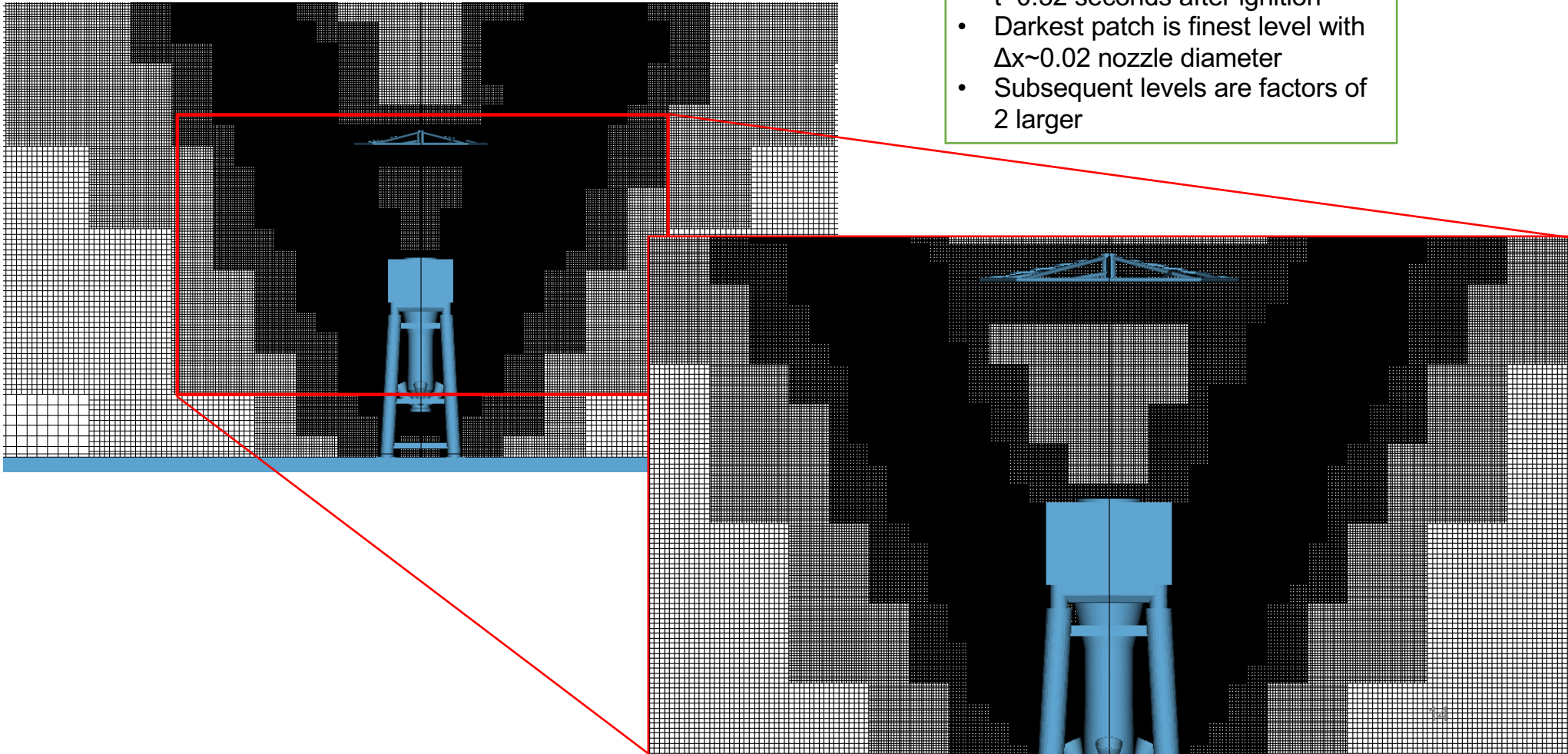
HPC Resources

1. Latest simulations ran for 30 days on 3000-4000 cores with 600-800 million grid points, for 400,000+ time steps at 4th order accuracy in time, 5th in space

2. Each simulation creates roughly 100 TB of volume data, and 100 GB of surface data (vehicle and cut planes)

3. Actively working to refactor code to increase parallel efficiency and strong scaling so we can further reduce turnaround time, or obtain longer acoustic samples within same time

Predict Loads for QM-1 Abort Motor Test
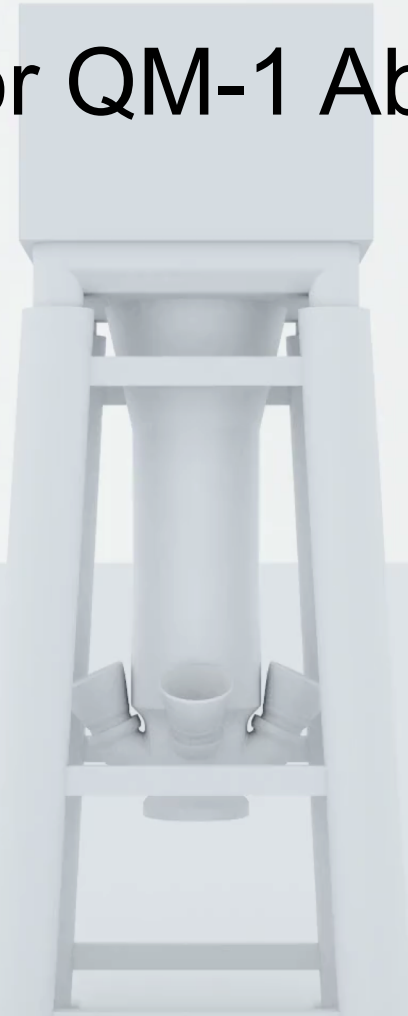
Rendering of the Orion Launch Abort System (LAS) qualification ground test (QM1) simulated using LAVA Cartesian with adaptive mesh refinement (AMR). Video showcases the turbulent structures resolved in the plumes colored by gauge pressure. Each pixel turning from blue to white to red indicates an acoustic waves passing through that can impinge on the apparatus and cause vibrations. We provided loads on heat shield fixture and crane to help test designers ensure safety of the test and reduce risk in data collection.

Launch Abort Motor
Qualification Motor (QM-1)
Static Test

June 15 2017

Orbital ATK

Post QM-1 Abort Motor Test Validation
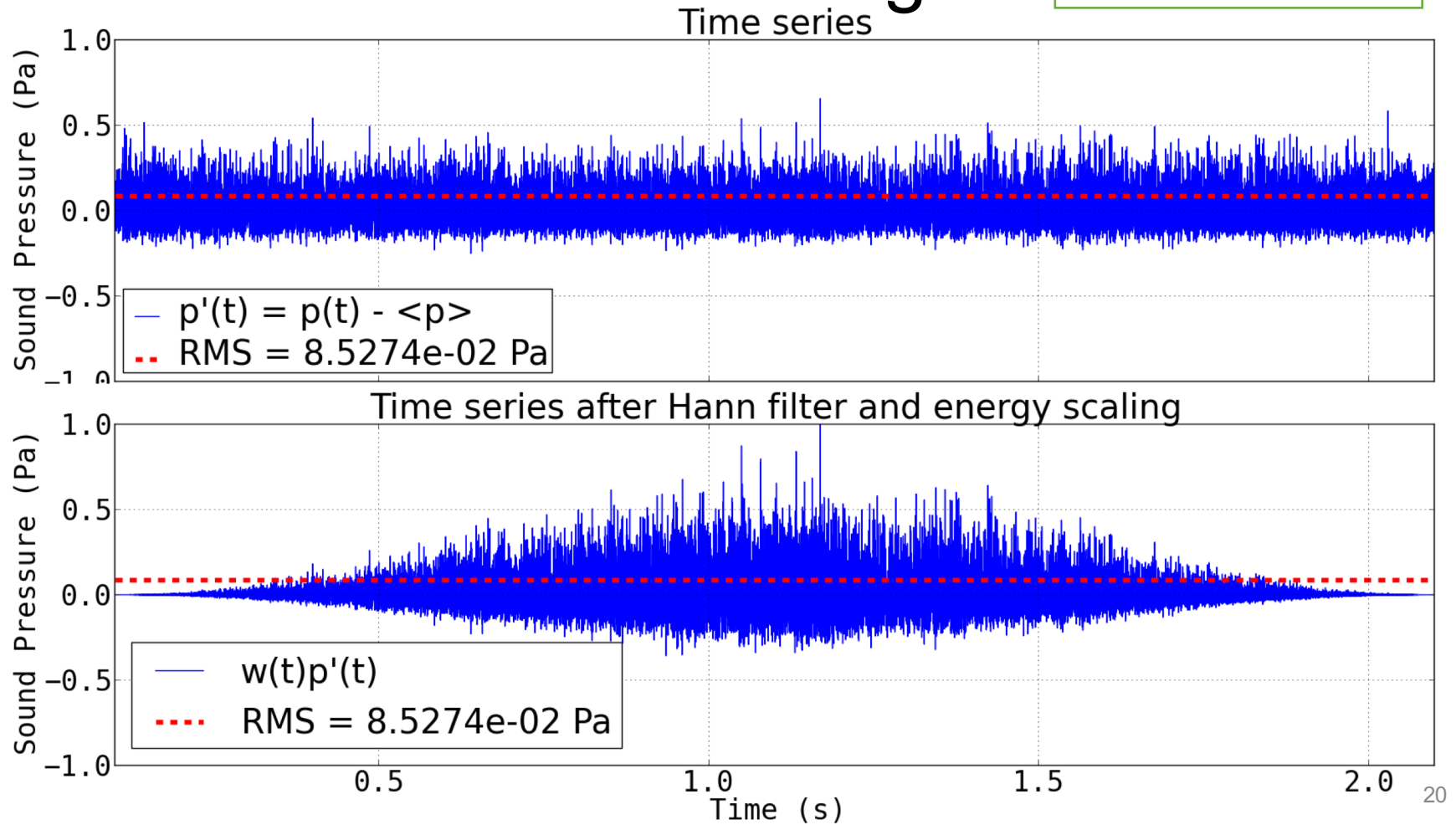
Ignition Overpressure (IOP) versus Time

- QM1 Measurements
- LAVA QM1v1 Simulation

*Discrepancy mainly due to difference in motor boundary conditions compared to measurements

Acoustics Post-Processing

Acoustics Post-Processing
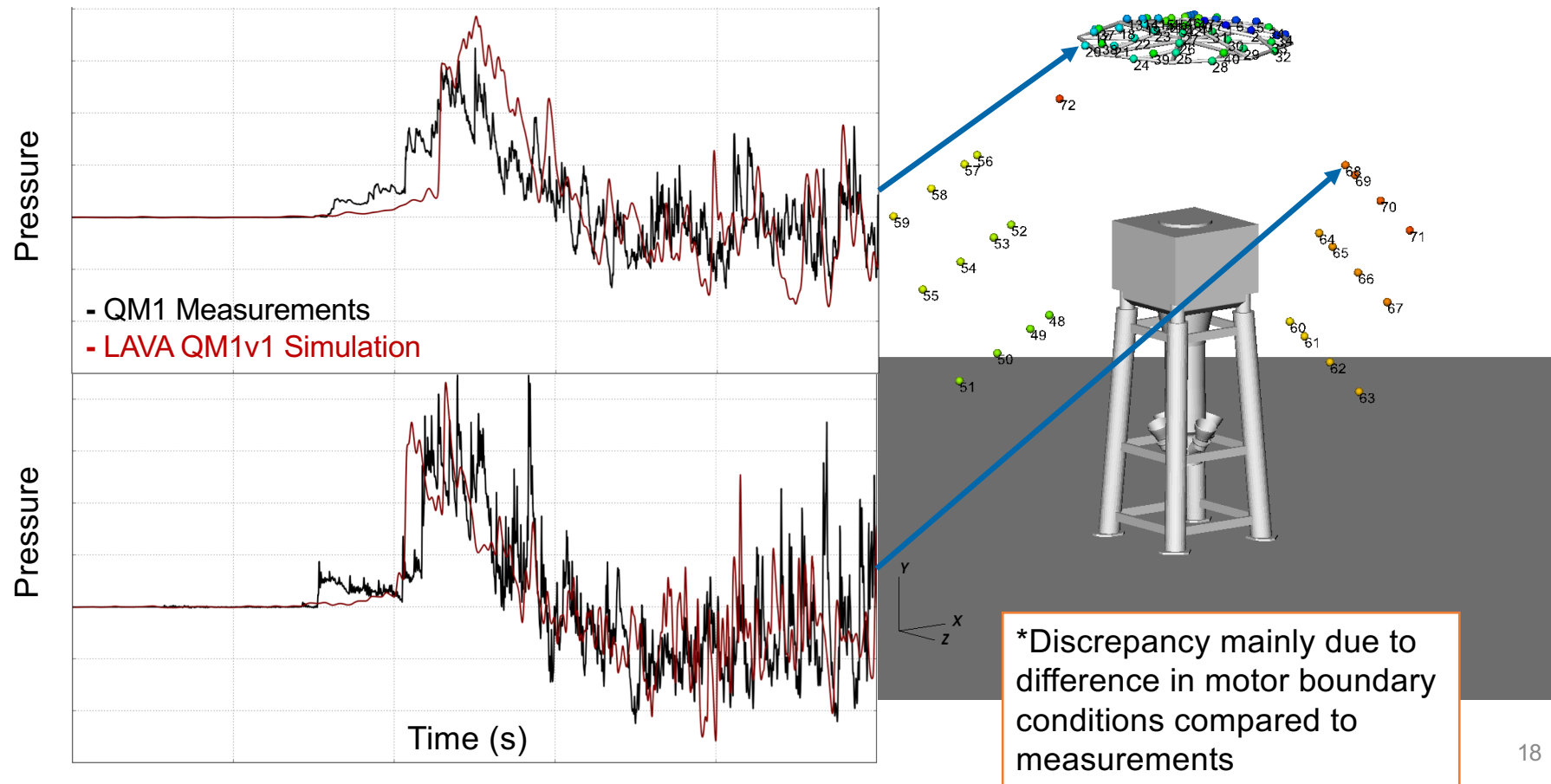
Acoustics Post-Processing
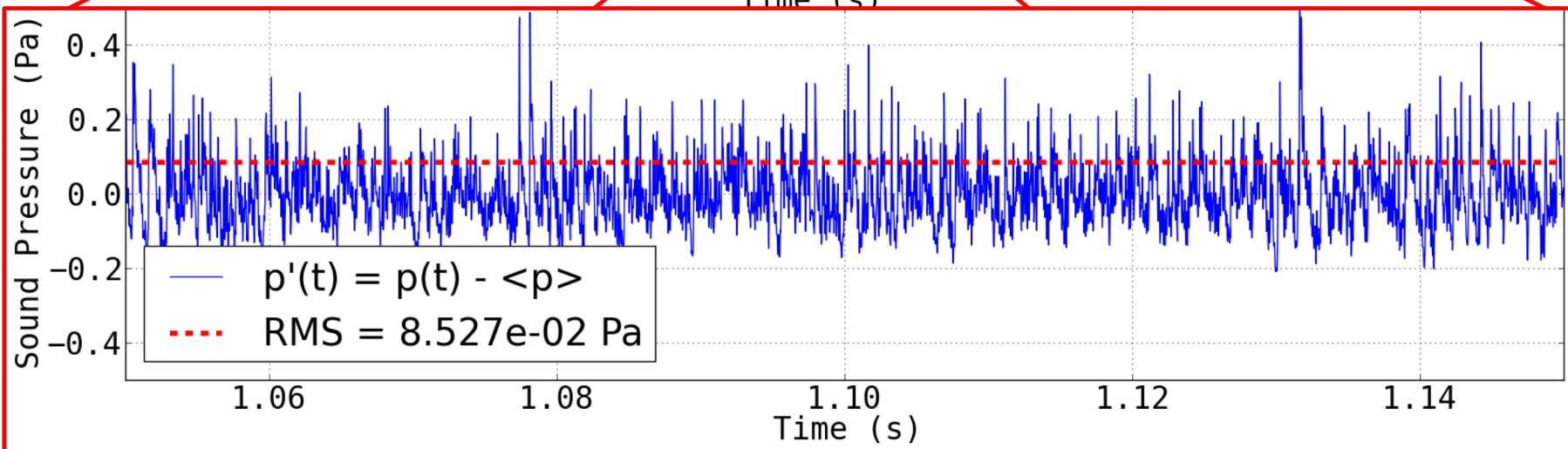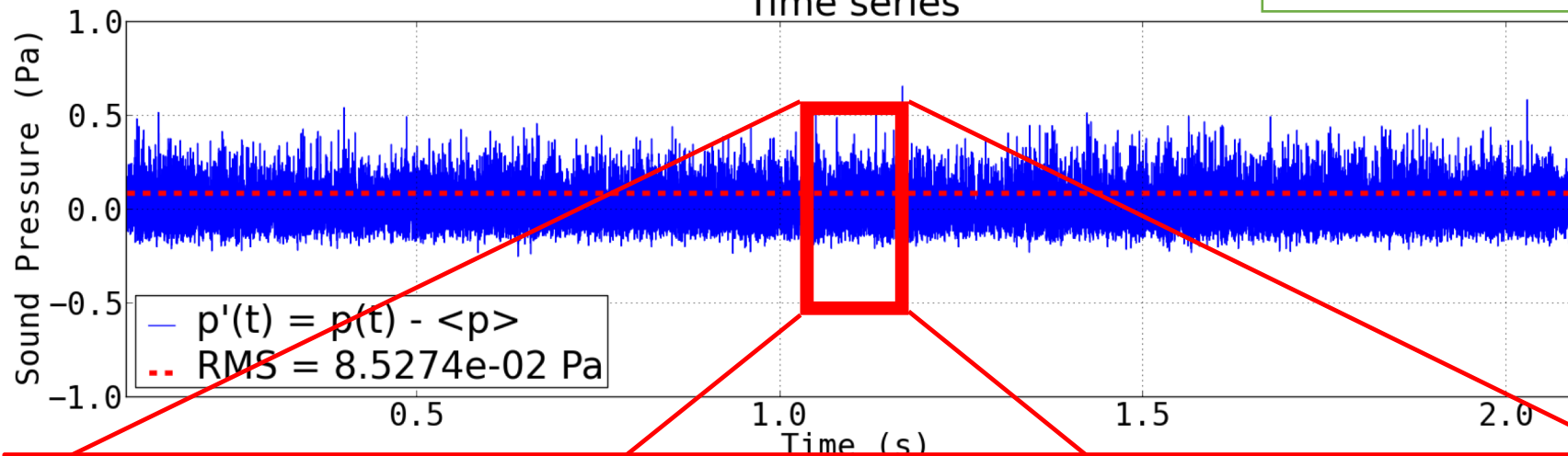
Time series after Hann filter and energy scaling

1. Make signal periodic

Sound Pressure (Pa) vs Time (s)

Legend:
- w(t)p'(t)
- RMS = 8.5274e-02 Pa

Scale to 1
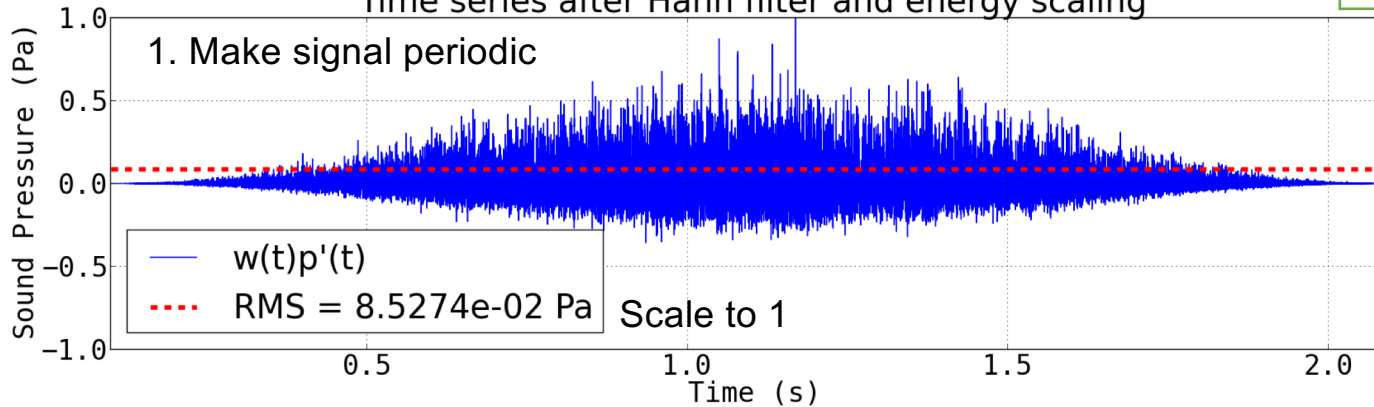
Overall Sound Pressure Level (OASPL)

$$\text{OASPL} = 10\log\left(\frac{(RMS)^2}{p_{ref}^2}\right)$$

→ OASPL = 72.58 dB

Narrow-band spectrum

2. Transform to frequency domain

Sound Pressure Level (dB) vs Frequency (Hz)

Legend:
- SPL(k)
- OASPL = 72.58 dB

1/3-octave band spectrum

3. Filter by 1/3 octave band

Sound Pressure Level (dB) vs Frequency (Hz)

Legend:
- SPL(k)
- BSPL(k)
- OASPL = 72.58 dB
- OASPL = 72.58 dB

Range of interest
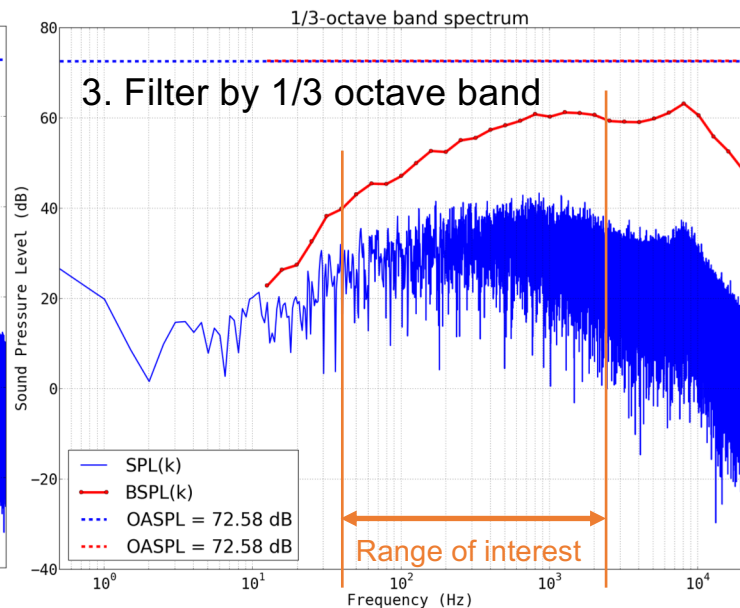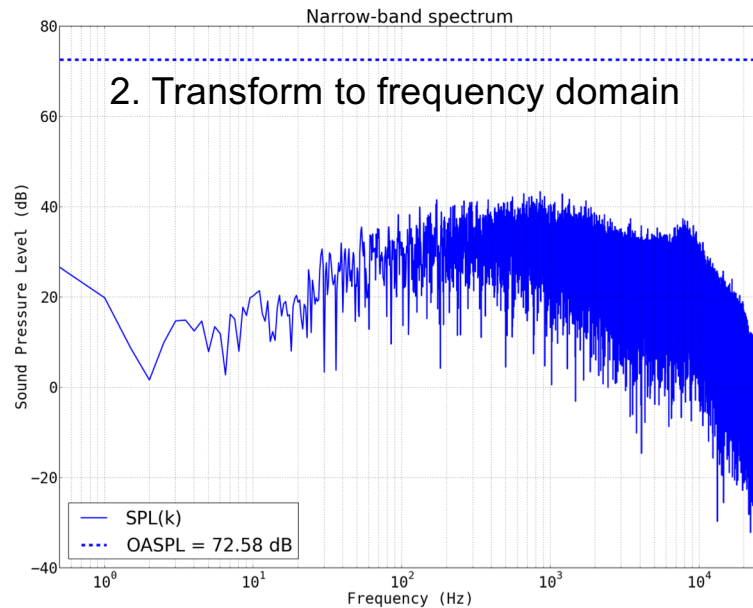
$$\text{SPL(k)} = 10\log\left(\frac{P(k)\,\Delta f}{p_{ref}^2}\right)$$

$$\text{BSPL}(\hat{k}) = 10\log\left(\frac{\sum_{k=k_s(\hat{k})}^{k_e(\hat{k})} P(k)\,\Delta f}{p_{ref}^2}\right)$$

$$\text{OASPL} = 10\log\left(\frac{\sum_{k=0}^{N} P(k)\,\Delta f}{p_{ref}^2}\right)$$

$$\text{OASPL} = 10\log\left(\frac{\sum_{\hat{k}=0}^{N}\sum_{k=k_s(\hat{k})}^{k_e(\hat{k})} P(k)\,\Delta f}{p_{ref}^2}\right)$$
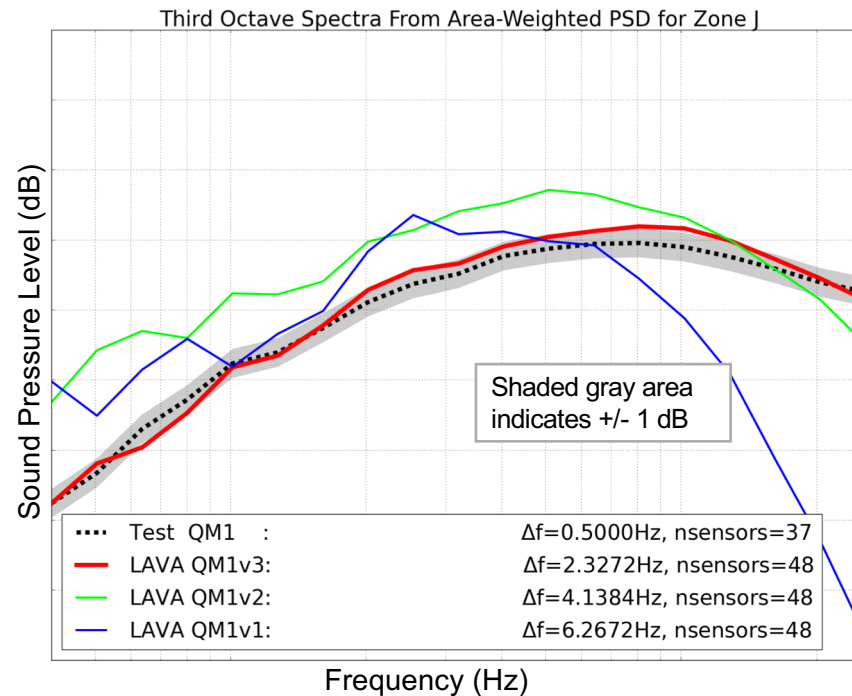
where
P(k) is the power spectral density
(Pa^2/Hz) at frequency k (Hz)

Post QM-1 Abort Motor Test Validation

Heat Shield Area-Weighted Kulite Acoustics

Third Octave Spectra From Area-Weighted PSD for Zone J

Sound Pressure Level (dB) vs Frequency (Hz)

Shaded gray area indicates +/- 1 dB

···· Test QM1 :	Δf=0.5000Hz, nsensors=37
— LAVA QM1v3:	Δf=2.3272Hz, nsensors=48
— LAVA QM1v2:	Δf=4.1384Hz, nsensors=48
— LAVA QM1v1:	Δf=6.2672Hz, nsensors=48

Simulations:
- QM1v1 had insufficient resolution in heat shield region to capture content beyond 1 kHz
- QM1v2 used target thrust from ballistics as motor boundary condition (18% higher than measured in QM1 Test)
- QM1v3 used the measured thrust, improved refinement regions with no AMR, no SEM, and longer time integration

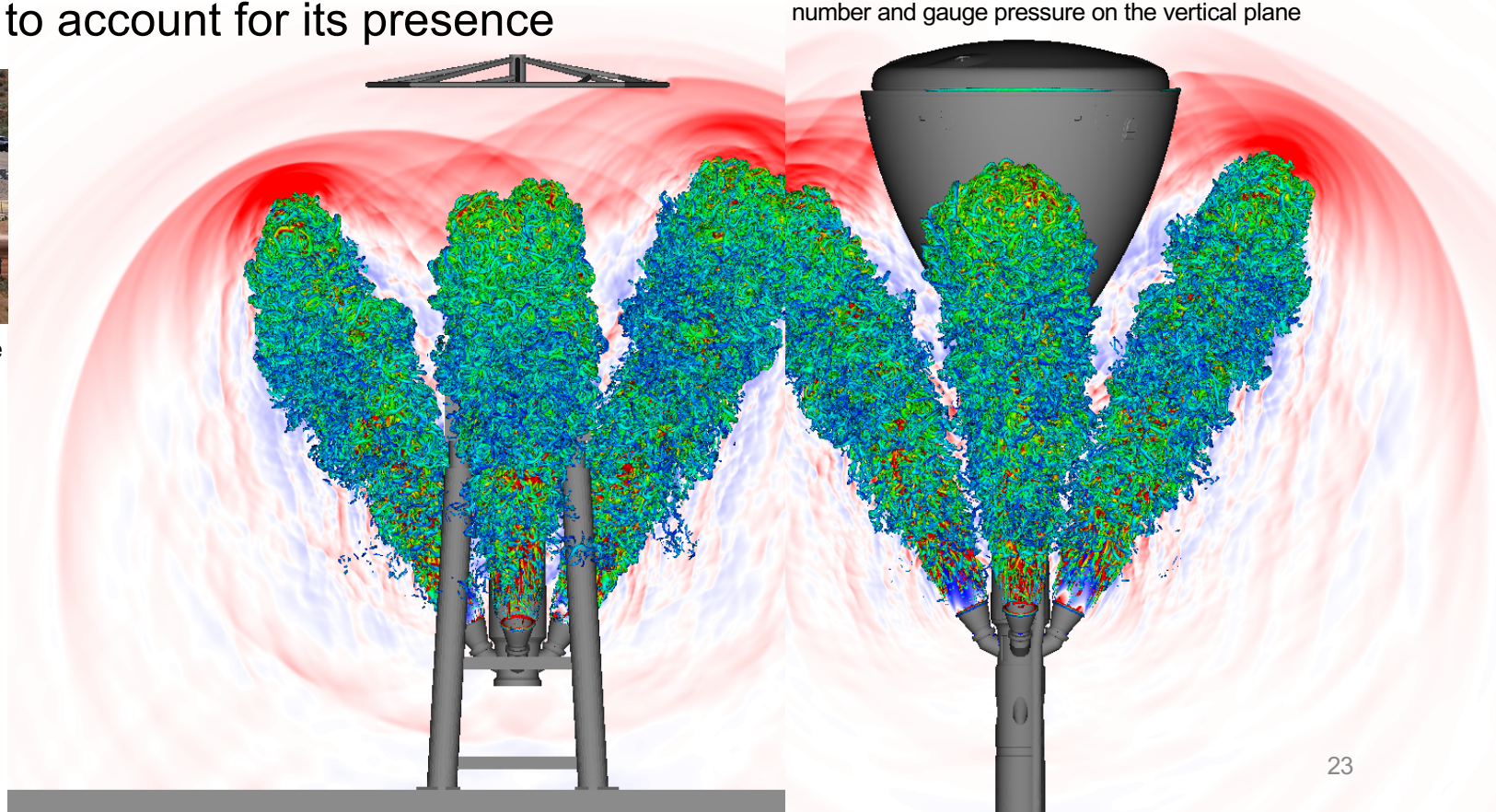## Heat Shield Kulite Sensors (microphones)

Face T1 Small

Small

Large, face: T2

Large, Face Block House

22
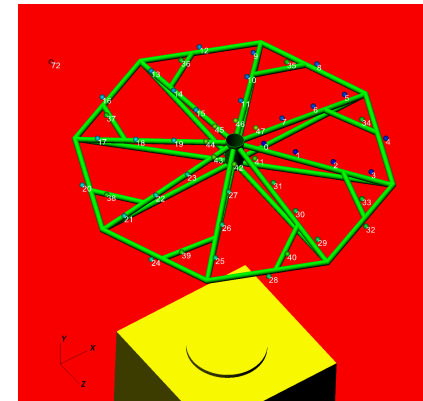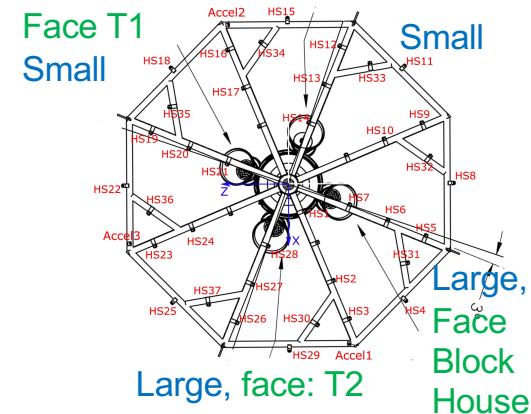
Launch Abort Vehicle Simulations

- LAV was missing from QM1 test

- Use CFD to account for its presence

Renderings of QM1 test and LAV pad abort simulations with iso-surfaces of Q-criterion colored by Mach number and gauge pressure on the vertical plane
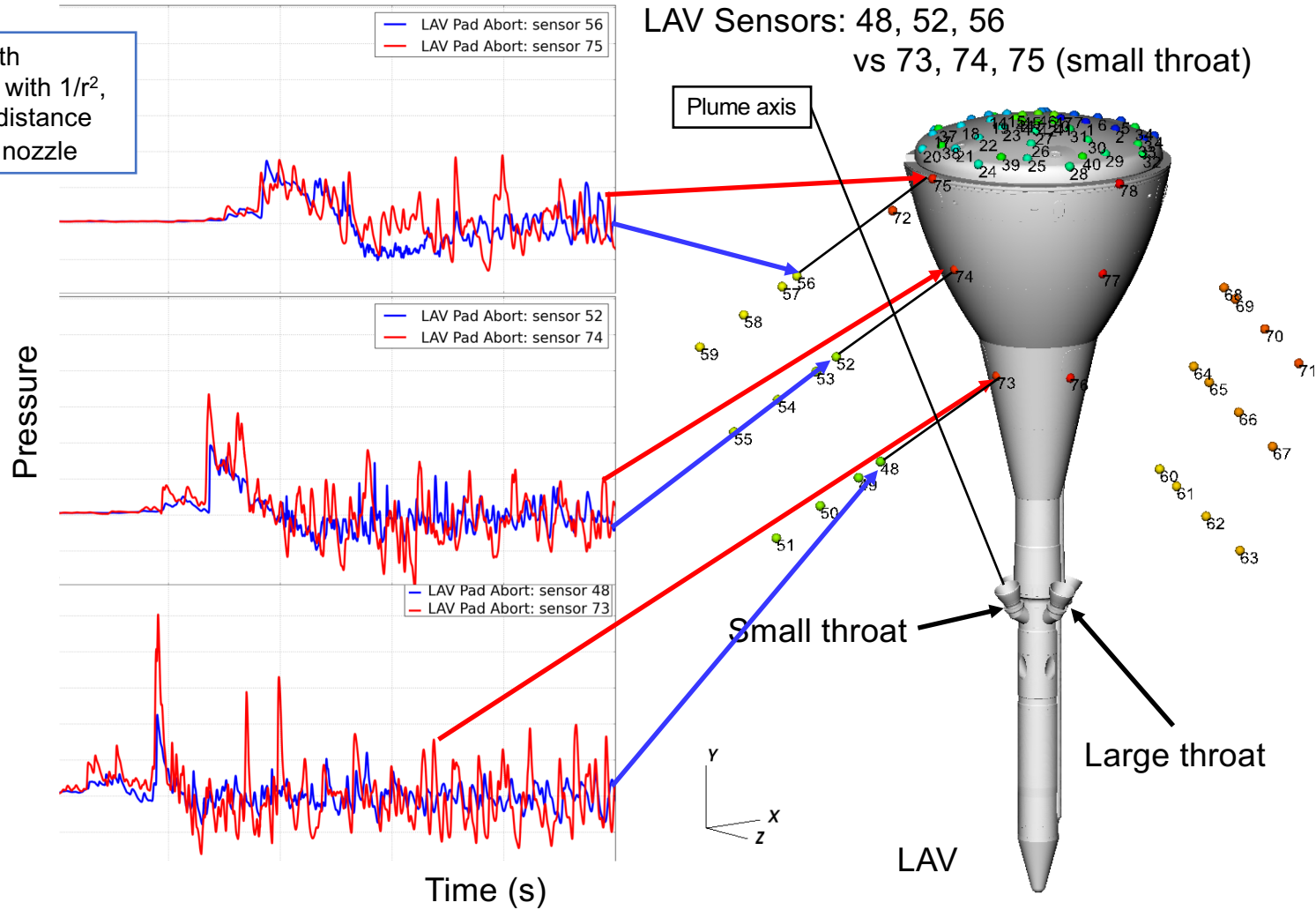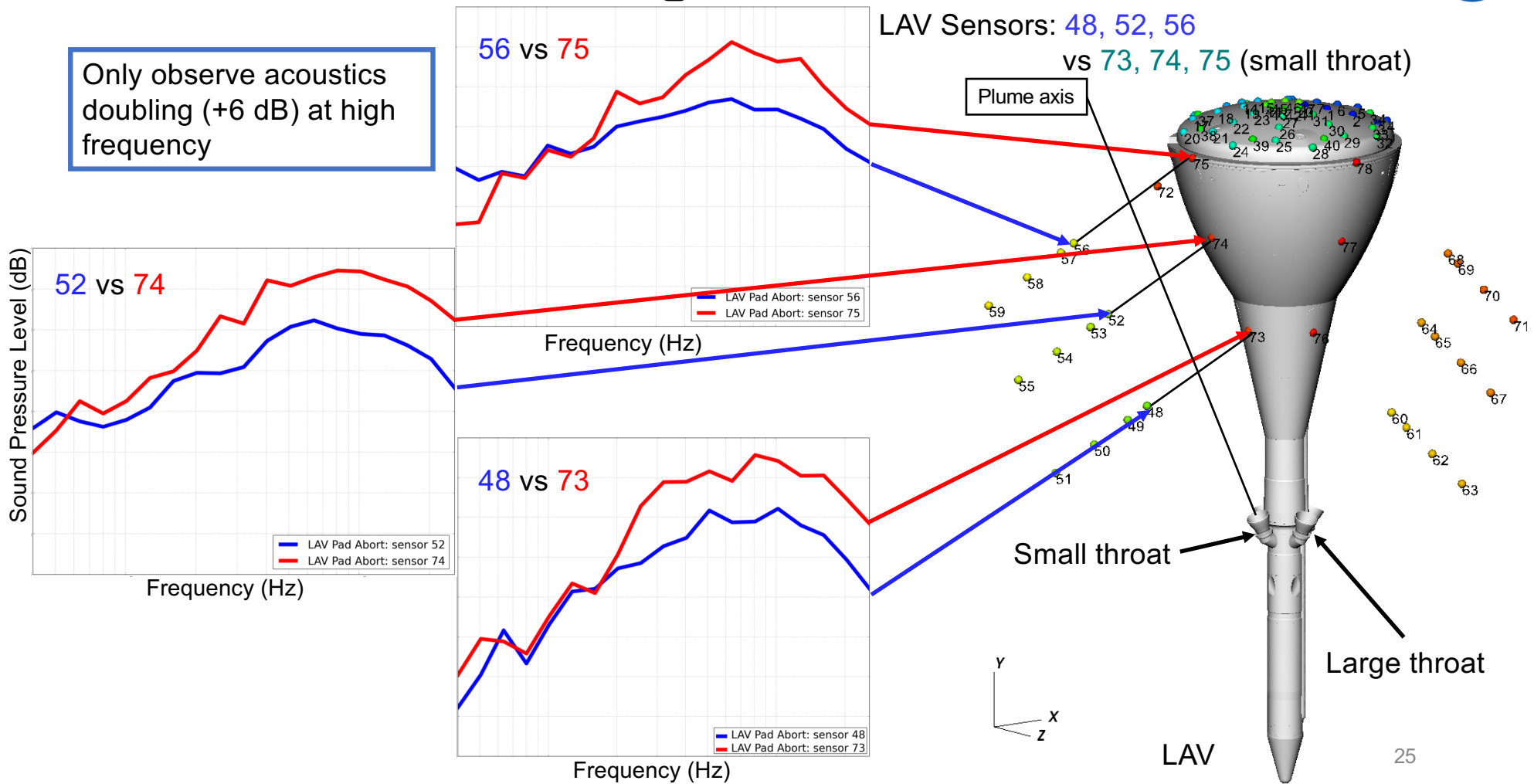

QM1 test photos for reference

Pressure Doubling on LAV Surface

IOP strength diminishes with $1/r^2$, where r is distance away from nozzle

LAV Sensors: 48, 52, 56 vs 73, 74, 75 (small throat)

Plume axis

Pressure

Time (s)

LAV Pad Abort: sensor 56
LAV Pad Abort: sensor 75

LAV Pad Abort: sensor 52
LAV Pad Abort: sensor 74

LAV Pad Abort: sensor 48
LAV Pad Abort: sensor 73

Small throat

Large throat

LAV

Acoustics Doubling on LAV Surface

Only observe acoustics doubling (+6 dB) at high frequency

56 vs 75

LAV Sensors: 48, 52, 56
vs 73, 74, 75 (small throat)

Plume axis

52 vs 74

Sound Pressure Level (dB)

Frequency (Hz)

LAV Pad Abort: sensor 52
LAV Pad Abort: sensor 74

Frequency (Hz)

LAV Pad Abort: sensor 56
LAV Pad Abort: sensor 75

48 vs 73

Frequency (Hz)

LAV Pad Abort: sensor 48
LAV Pad Abort: sensor 73

Small throat

Large throat

LAV

Investigating Ascent Abort Scenarios
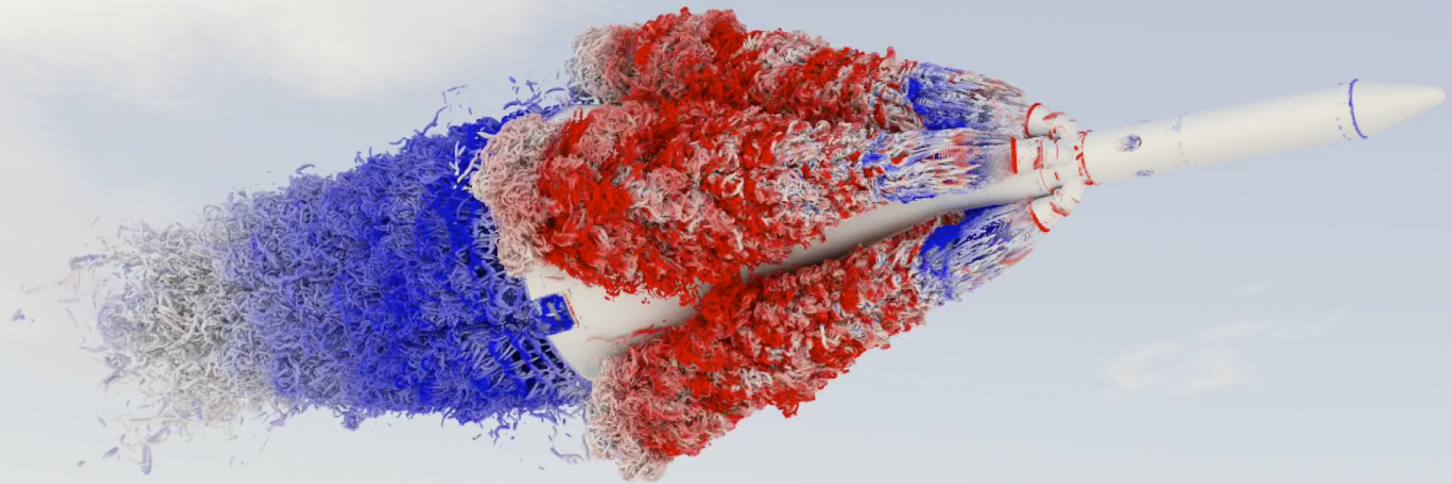
Rendering of the Orion Launch Abort Vehicle (LAV) during an ascent abort simulation where the vehicle is traveling at low supersonic speeds when abort is triggered. Video showcases the turbulent structures resolved in the plumes colored by gauge pressure. Each pixel turning from blue to white to red indicates an acoustic wave passing through that can impinge on the apparatus and cause vibrations. The delta difference in unsteady loads between the QM-1 and LAV at different flight conditions is used to determine vehicle detailed design requirements.

Investigating Ascent Abort Scenarios

Effect of velocity and altitude on Overall Sound Pressure Level

Pad Abort
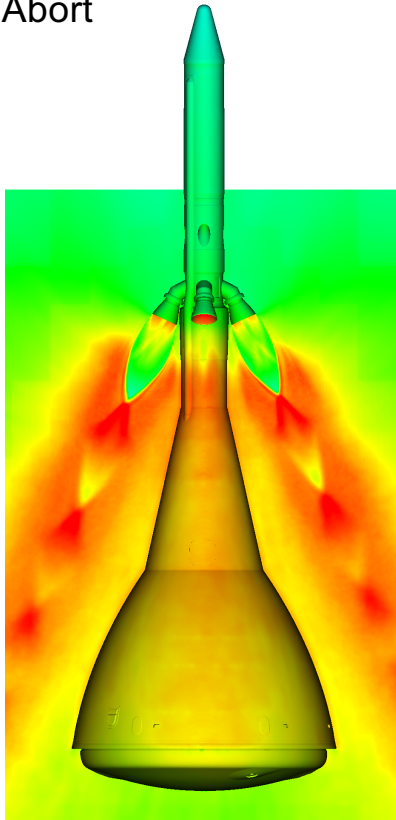
Low Supersonic Abort
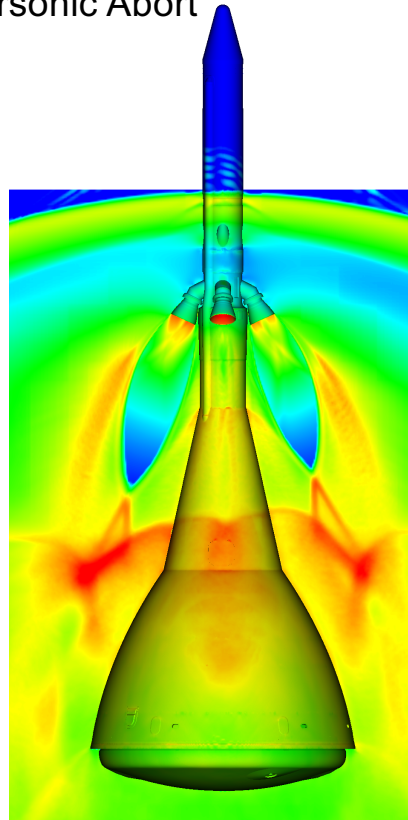
Supersonic Abort
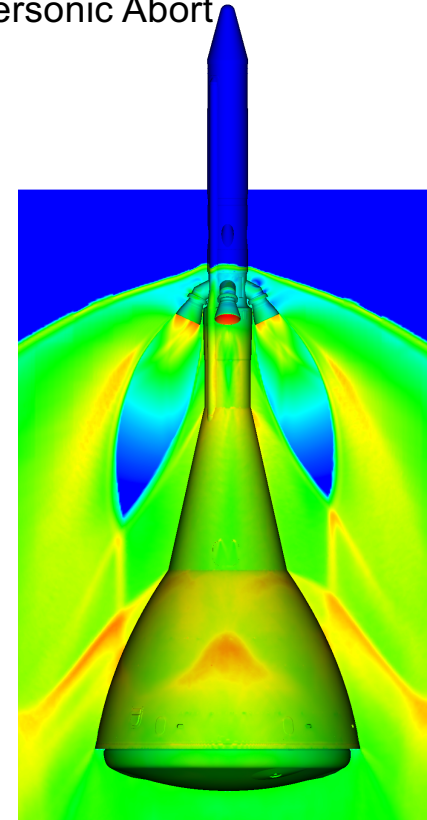
Colormap is the same across all plots (blue is low, red is high)

Wind Tunnel Experimental Validation

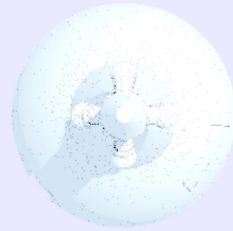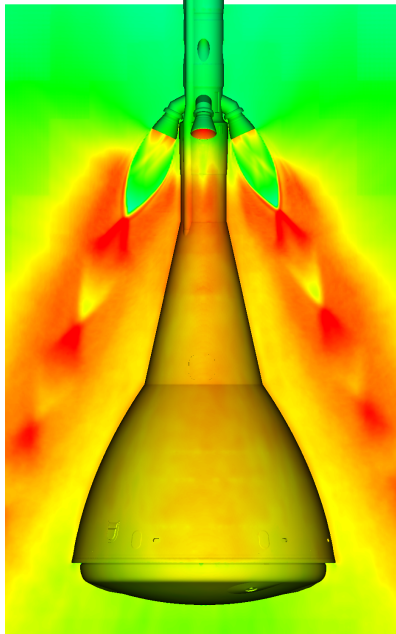Transonic ascent abort at moderate angle of attack and side slip
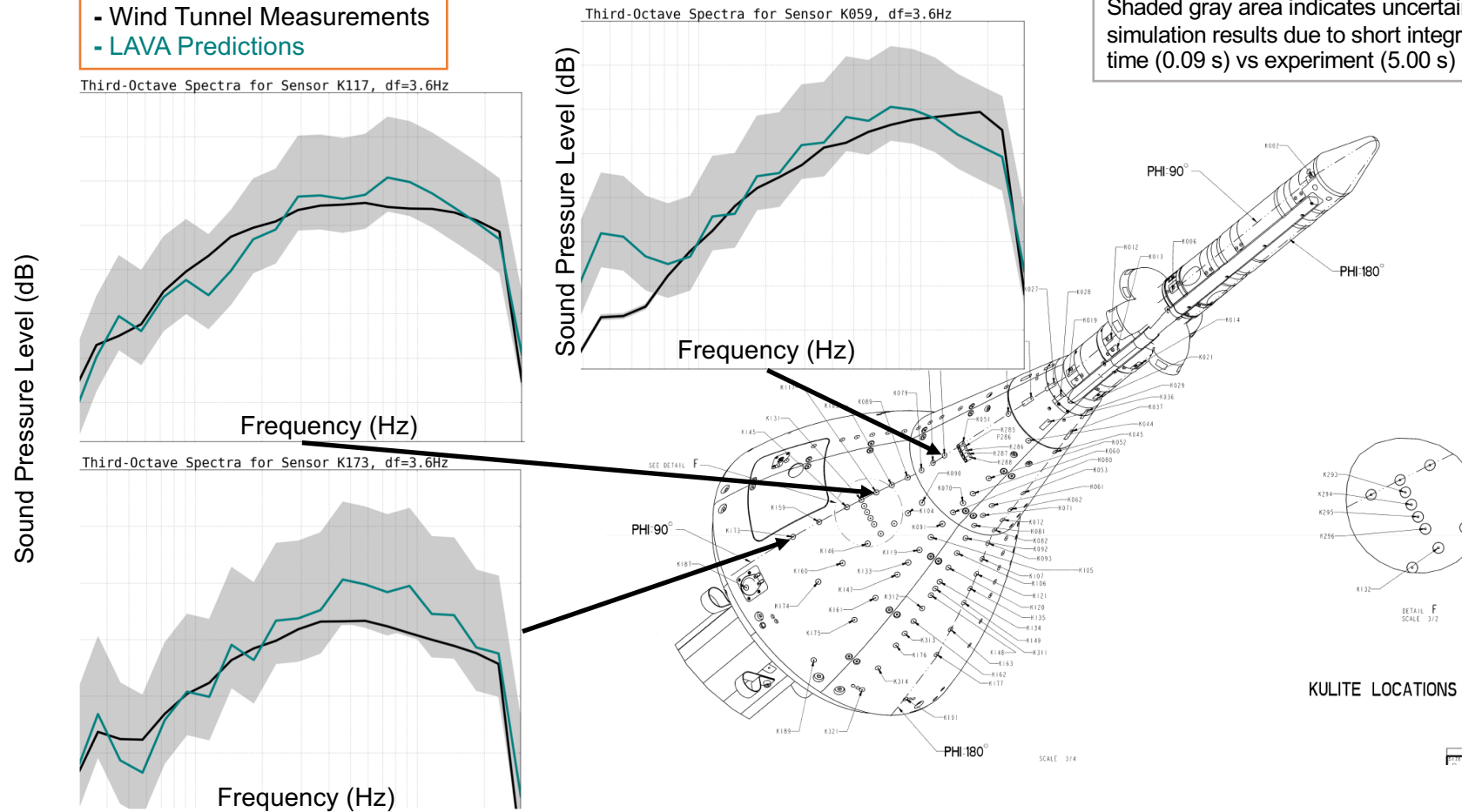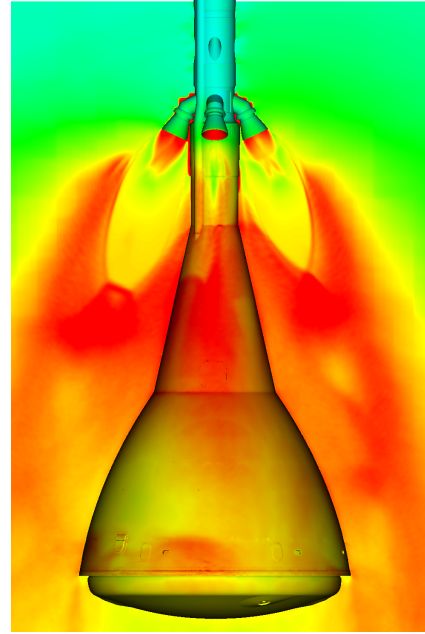
Exploring High Angles of Attack

Volume rendering of temperature for LAV transonic ascent abort at high angle of attack

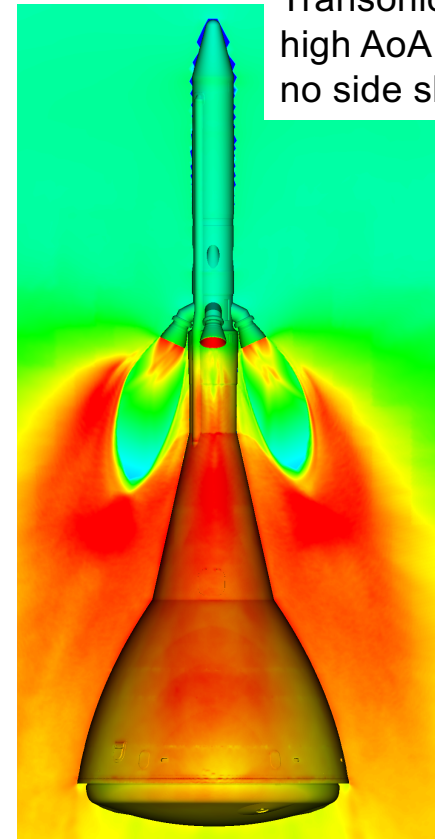# Effect of Angle of Attack on Acoustics

Pad abort
no AoA
no side-slip

Transonic abort
moderate AoA
and side-slip

flow
direction

Transonic abort
high AoA
no side slip

Flow for AoA is INTO the plane, side-slip is flow from right to left

*Colormap is the same on all plots

Lessons Learned: Keys to Success

- High-order space-time scheme to reduce resolution req's

- Solution-adaptive mesh refinement for capturing IOP

- Uninterrupted fine cells from turbulent shear layer (noise source) to vehicle/sensors of interest for acoustics

- High parallel efficiency/scalability to enable long integration time for converging to smooth acoustic spectra

→ Even for other grid paradigms, much of the mesh would need to be near-isotropic and solved with a small time step…

Summary

- Performed 10 scale-resolving simulations to support Orion Loads and Dynamics team and Orion project

- Helped enhance safety and reduce risk for QM-1 test

- Validated CFD with post-test data and wind tunnel test measurements

- Investigated effects of Mach number on acoustic environment

- Explored high angles of attack to reduce uncertainty in design process

Acknowledgments

- This work is funded by NASA Orion project
- Computer resources provided by NASA Advanced Supercomputing (NAS) Facility
- NASA Orion Loads and Dynamics team:
  - Quyen Jones
  - Jayanta Panda
  - Vincent Fogt
  - Kenneth Fiorelli
- NAS Visualization Team:
  - Timothy Sandstrom
- LAVA Team:
  - for providing insights and lessons learned from other projects

Questions?
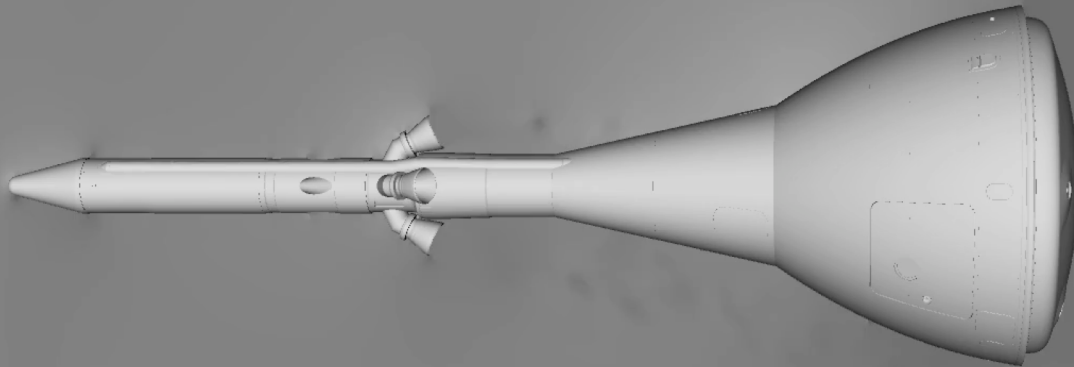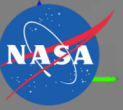
Pressure on the vertical plane (white is high, black is low) for LAV transonic ascent abort at high angle of attack
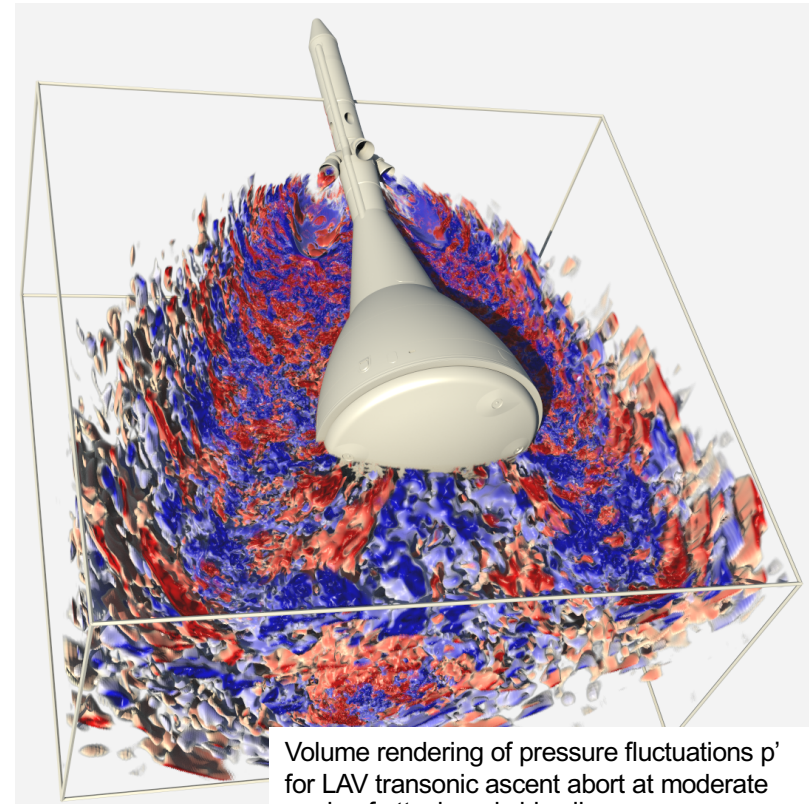
Future Work:
Flight Test Validation
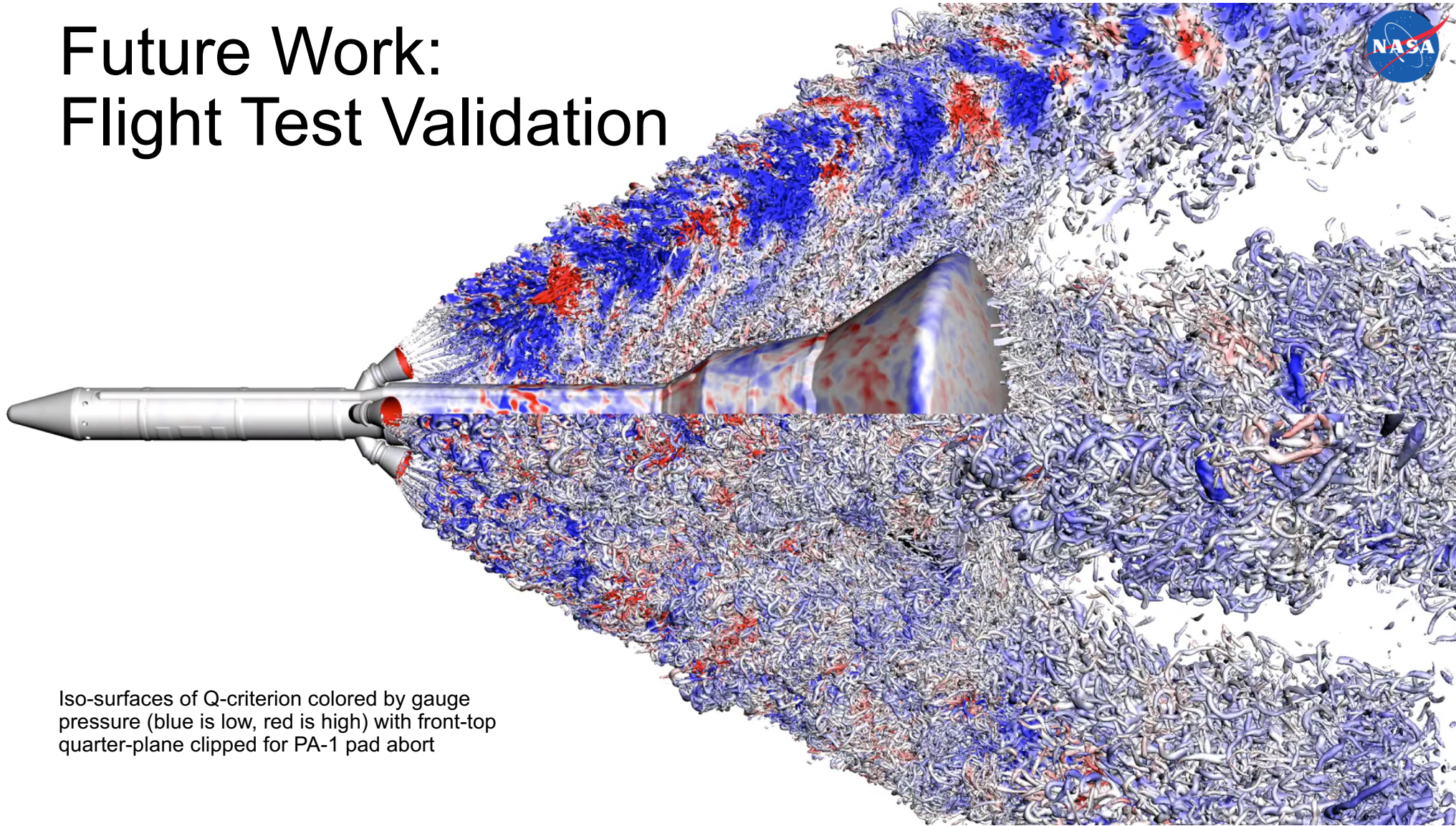
Iso-surfaces of Q-criterion colored by gauge
pressure (blue is low, red is high) with front-top
quarter-plane clipped for PA-1 pad abort

# APPENDIX

Acoustic Visualization Technique

1. Interpolate pressure from adaptive-mesh-refinement solution onto evenly-spaced mesh box shown on right

2. Accumulate time average of pressure at every point on that box

3. Compute $p' = p - <p>$ at every point and every time step

4. Render volume of p' using a smooth transfer function that looks like $|p'|>\Delta p$, where Δp is set by user

Volume rendering of pressure fluctuations p' for LAV transonic ascent abort at moderate angle of attack and side slip
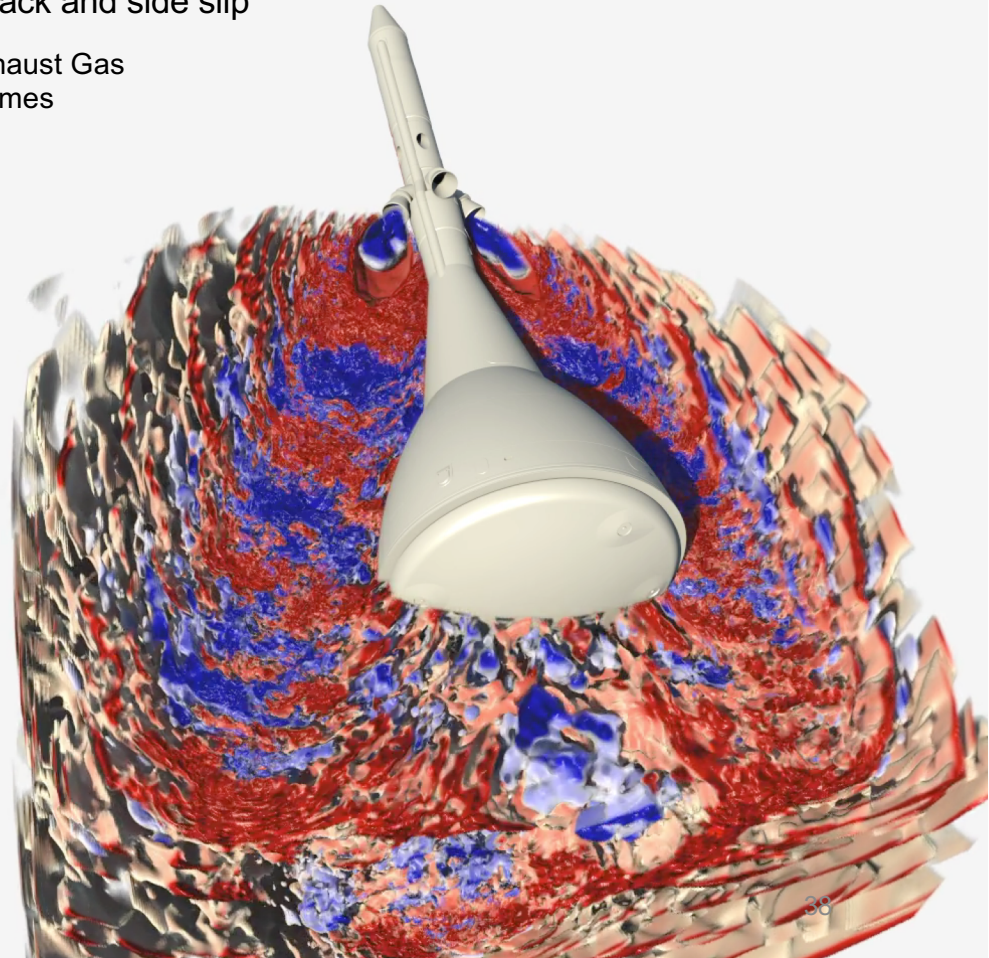
From Wind Tunnel To Flight Using CFD

Volume rendering of p' clipped at vertical plane for wind tunnel (left) and LAV (right) transonic ascent abort simulations at moderate angle of attack and side slip

Helium Plumes
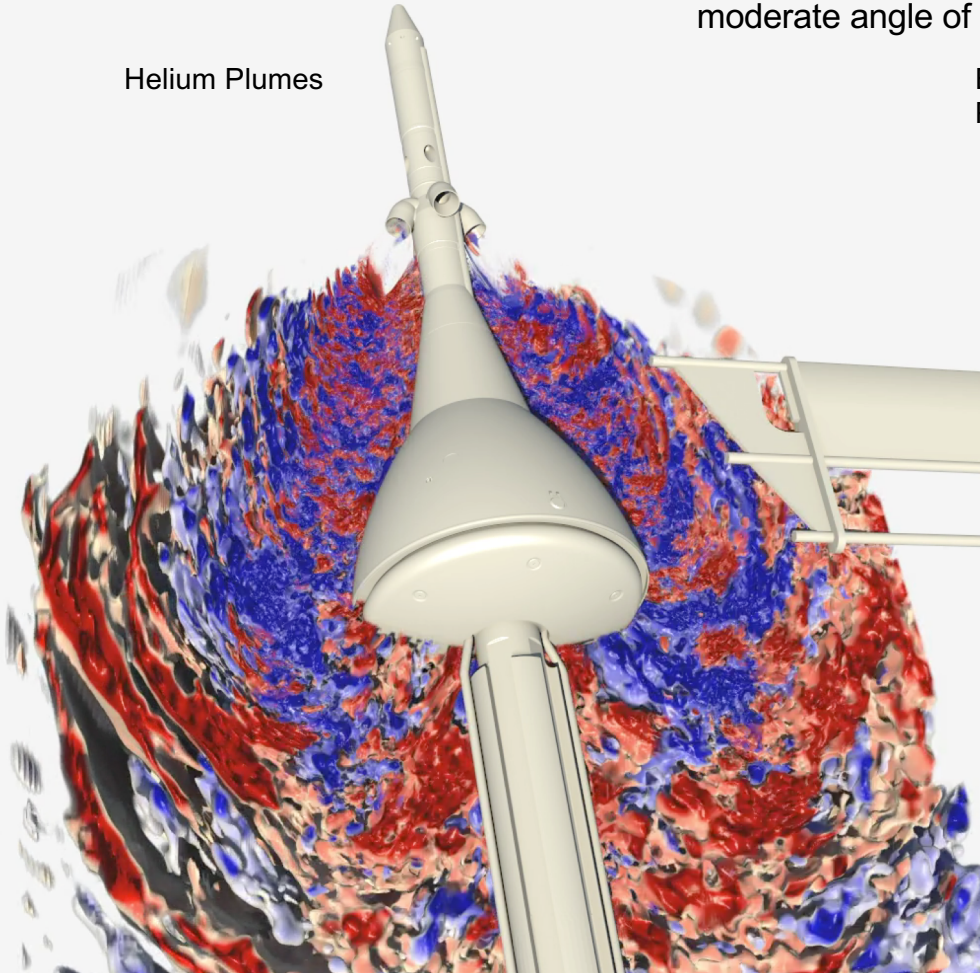
Exhaust Gas
Plumes

QM1 test at Orbital ATK facility in Utah

QM1 test at Orbital ATK facility in Utah

NFPA Towers

Crane

Completed Orion LAS LAVA Simulations

Case	Current Duration [s]	Acoustics Interval [s]
QM1v1	0.2280	0.148
LAV Pad Abort	0.5020	0.422
LAV Low Supersonic	0.3730	0.293
LAV Supersonic	0.3220	0.242
QM1v2	0.3210	0.241
LAV Transonic at moderate AoA	0.3700	0.290
80-AS Transonic at moderate AoA	0.090*	~0.60*
LAV Transonic at high AoA	0.3410	0.261
QM1v3	0.5235	0.430
PA-1 Pad Abort	0.5953	0.476

*With plume scaling, we have ~0.6 seconds of "flight" data

LAVA Simulations

Numerical Methodology

| Parameter	Previous	Latest	Benefit
Convective flux	5th order WENO	5th order WENO	-
Time integration	Explicit 4th order Runge-Kutta	Explicit 4th order Runge-Kutta	-
Time step	Fixed Courant Friedrichs Lewy number (CFL) = 0.5 $\rightarrow \Delta t \sim 1.6 \times 10^{-6}$ seconds	Fixed Time Step $\Delta t \sim 1.6 \times 10^{-6}$ seconds $\rightarrow$ CFL ~ 0.5	-
Inter-level time integration	Composite: all levels of the mesh are updated at each step, with the same Δt	Sub-cycled: only finest mesh level is updated at each step, the next finest is updated every other step with a dt twice as large	Better parallel efficiency & scaling (faster)
Adaptive Mesh Refinement (AMR)	Grid is adjusted every 10 steps to follow vorticity and pressure gradients	None – grid is user-defined	No re-gridding overhead, better capture turbulent pressure fluctuations
Total mesh size (x10^6)	~350	600-800	Similar resources and turnaround time
Motor Boundary Condition	Time-varying total conditions from ballistics (including IOP)	Fixed total conditions from experiment at 0.2 seconds	Faster to reach stationary state (reduces turnaround time)
Synthetic Eddy Method	Turbulence injected upstream of splitter (SEM)	None	No spurious noise near nozzles

Predict Loads for QM-1 Abort Motor Test
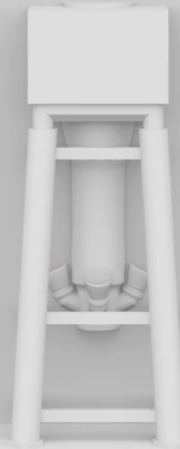
Passive particles colored by Mach number and gauge pressure on the vertical plane showing the propagation of the ignition overpressure wave
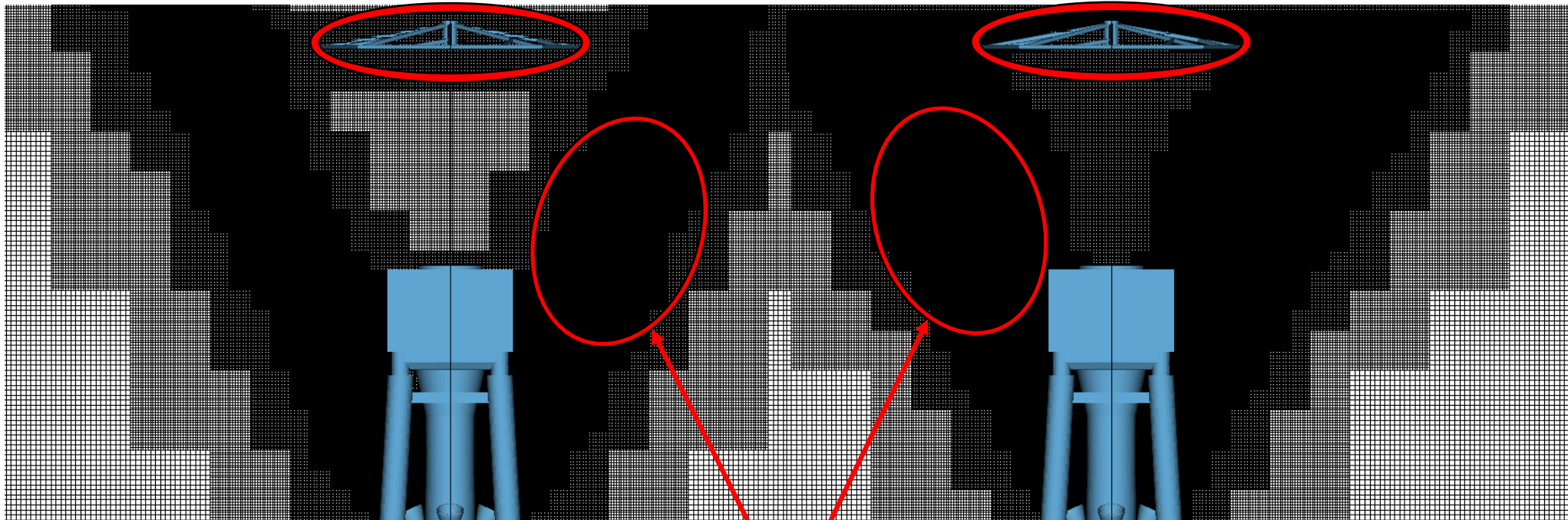
LAVA Simulations
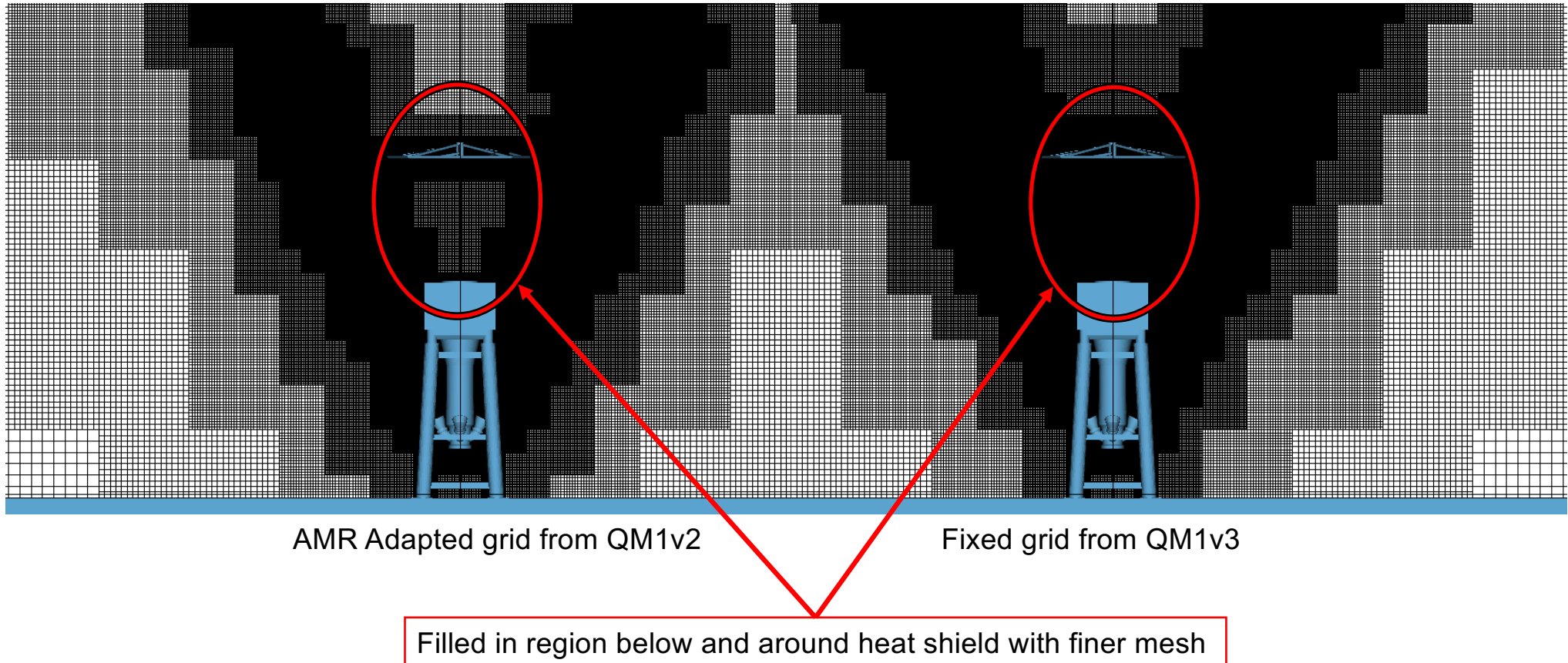
Numerical Methodology

AMR Adapted grid from QM1v2   Fixed grid from QM1v3

Filled in region below and around heat shield with finer mesh
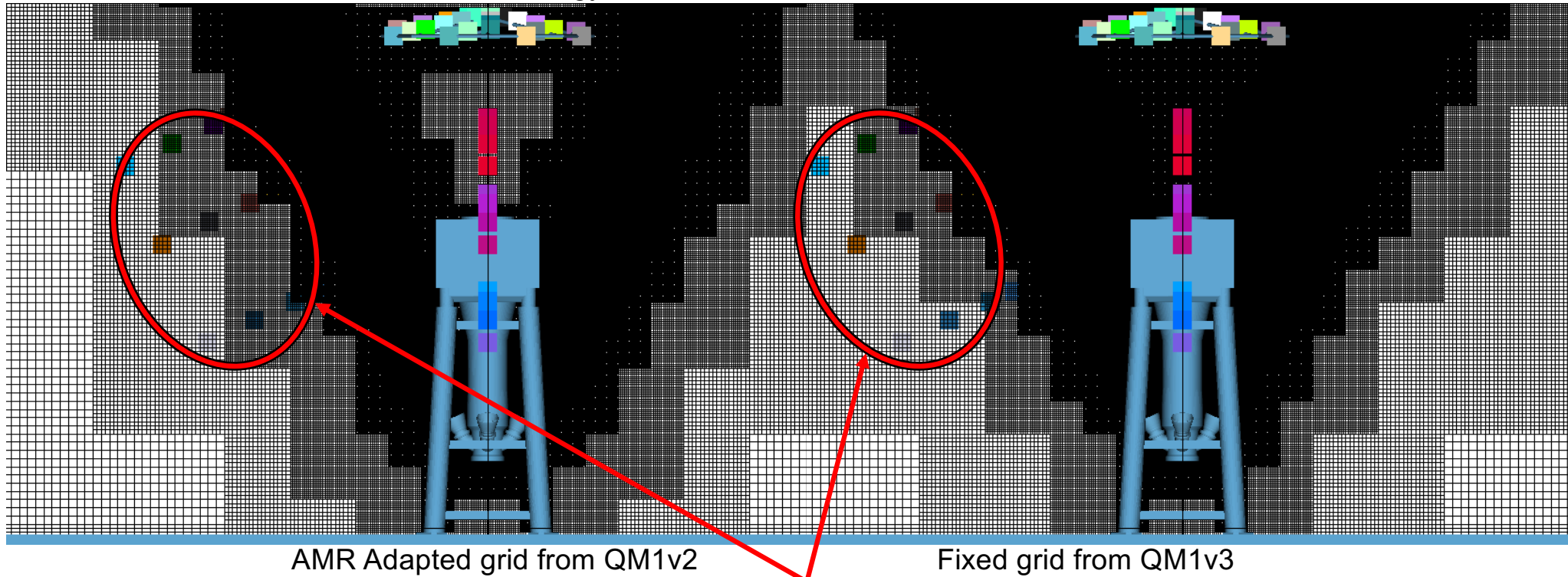
LAVA Simulations

Numerical Methodology

AMR Adapted grid from QM1v2   Fixed grid from QM1v3

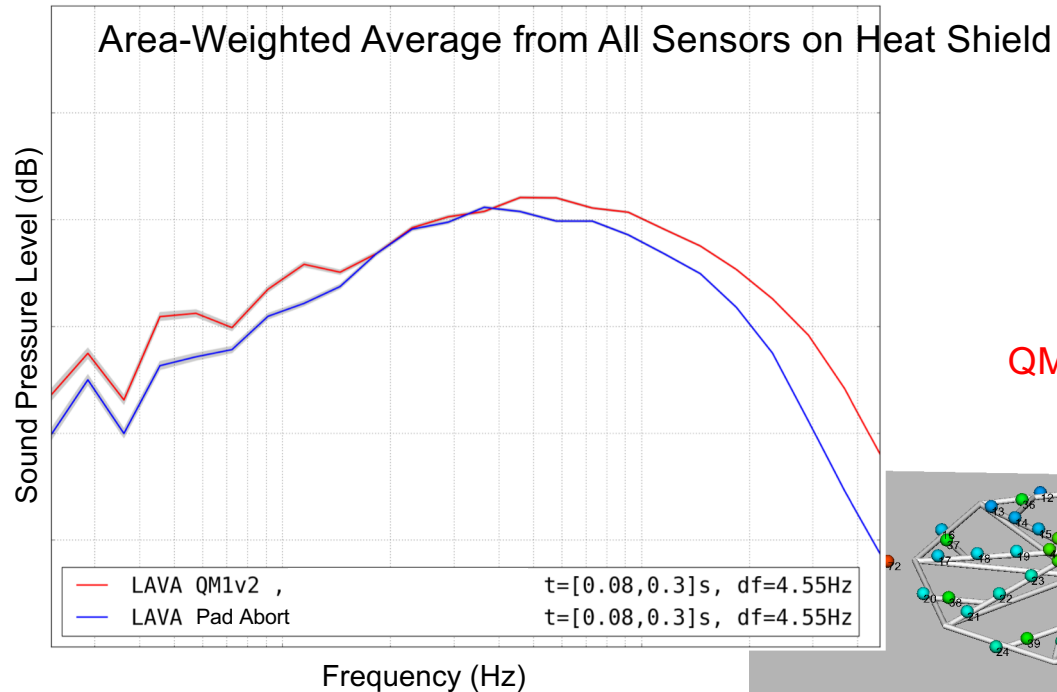Larger region of fine mesh around plume and heat shield

LAVA Simulations

AMR Adapted grid from QM1v2   Fixed grid from QM1v3

But NFPA sensors and inner ring heat shield sensors are
still not all covered by finest mesh
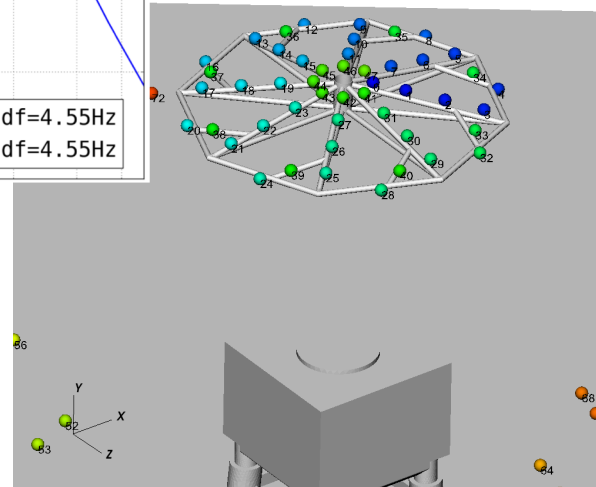→ reduces max frequency resolved by factor of 2 for those
sensors

Changes in Heat Shield Acoustics

Area-Weighted Average from All Sensors on Heat Shield

Sound Pressure Level (dB)

Frequency (Hz)

LAVA QM1v2 ,   t=[0.08,0.3]s, df=4.55Hz
LAVA Pad Abort   t=[0.08,0.3]s, df=4.55Hz

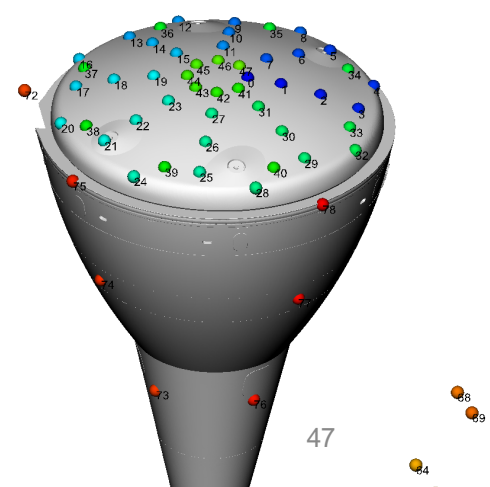Heat shield sees small reduction in levels due to shielding from the LAV

QM1

LAV Pad Abort

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From Wind Tunnel To Flight

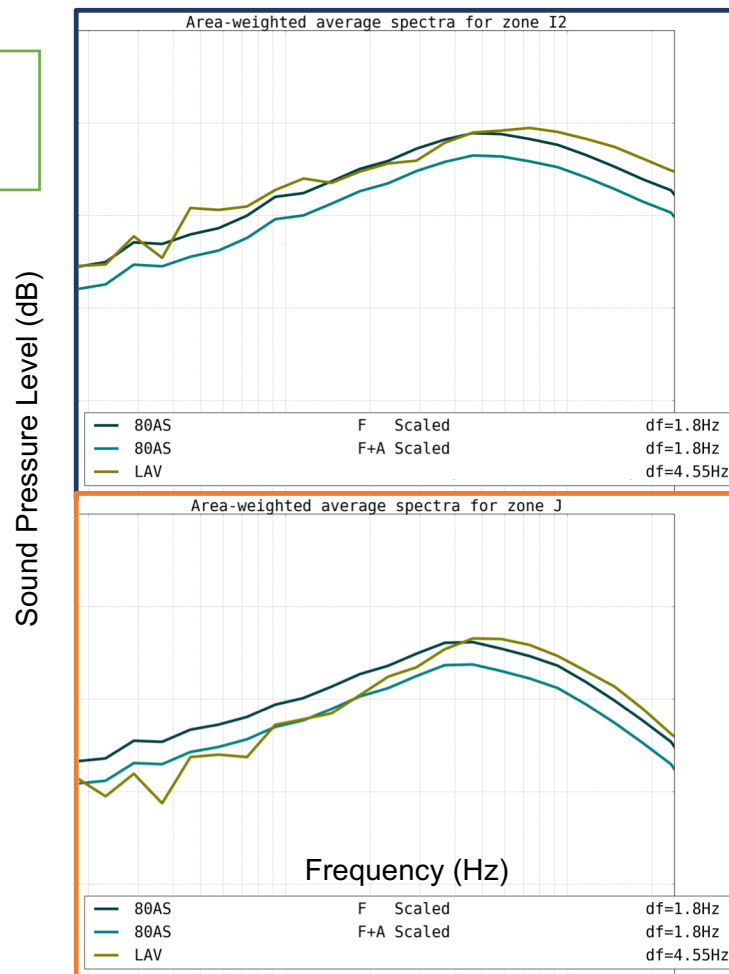**Overall Sound Pressure Level**

80AS Wind Tunnel Simulation with Helium Plumes at transonic speed with moderate AoA and side-slip

Orion LAV Flight Simulation with Exhaust Gas Plumes at transonic speed with moderate AoA and side-slip
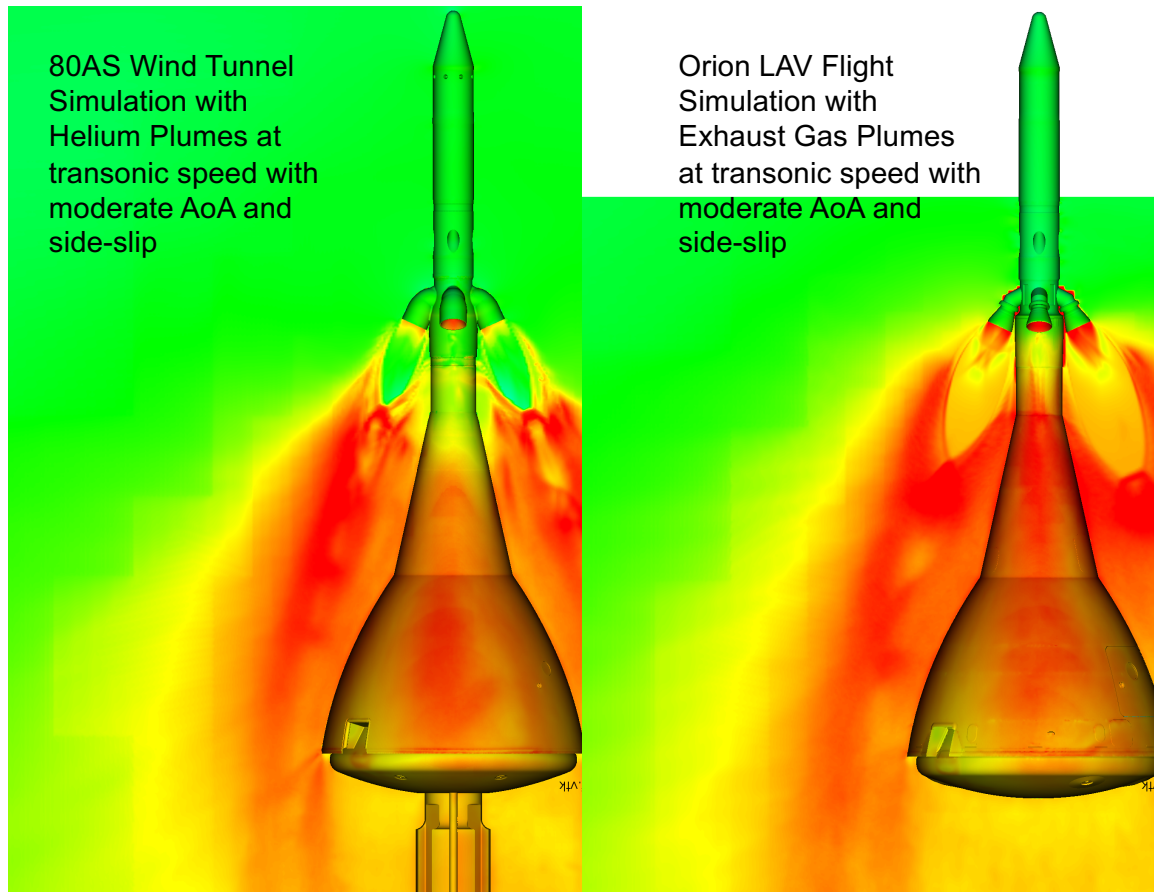
Acoustics: From Wind Tunnel to Flight
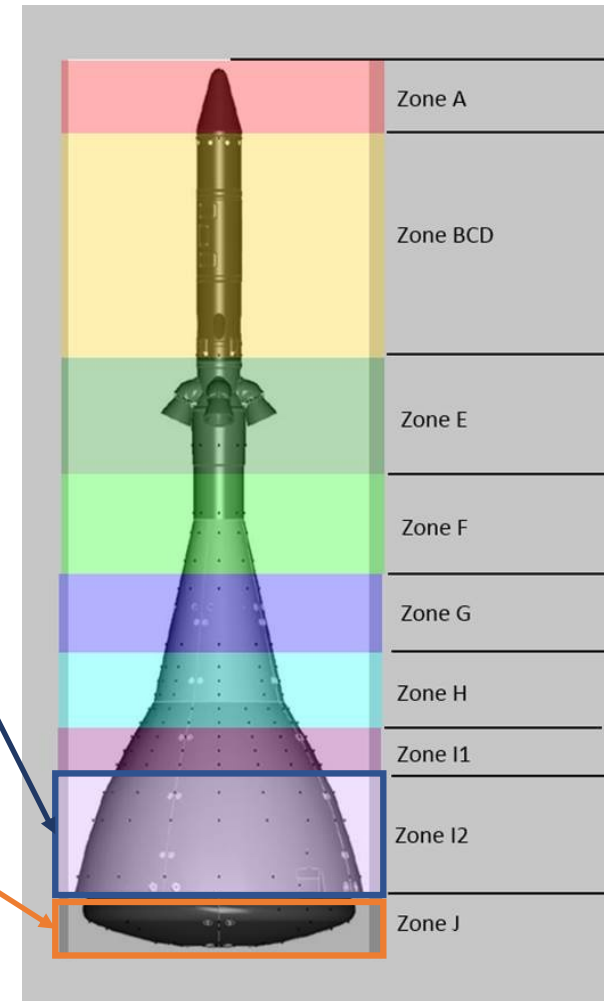
Lessons Learned

- Solution-based AMR is crucial to accurately capture IOP

- AMR has impact on turbulence spectrum and acoustics that is difficult to control and quantify → better to use it in initial simulation and then define fixed refinement zones

- Need finest mesh level wherever sensors or an important surface is located along with an unbroken connection to source of sound, otherwise, the high frequency content is lost due to jumps in mesh resolution

Lessons Learned (cont'd)

- Long time integration is key to obtaining smooth spectra that one can compare to experiments that are multiple seconds long → any algorithmic or parallel efficiency improvement that reduces turnaround time is worth implementing

- Robustness of immersed interface treatment and numerical flux is critical with hot, shocked plumes and thin nozzle lips

- Important to post-process the experimental data and CFD in the exact same way if possible to have apple-to-apples comparison, sometimes we keep some differences intentionally but it's important to know what the impact is on the comparisons